Improved Ferrite Biasing Scheme for Booster RF Cavities

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Abstract

A new engineering design of ferrite tuners for rapid-cycling-booster rf cavities is proposed. The basic concept is to divide a perpendicularly biased ferrite tuner into two (or more) successive or parallel sections which are magnetically biased in opposite directions. This approach aims at several improvements with respect to existing designs: (a) reduction of magnet weight, (b) lower eddy currents, (c) reduction (or cancellation) of magnetic fields on beam axis, and (d) possibility of increasing the tuner breakdown voltage by stepwise widening of airgaps between ferrite layers of successive tuner sections. Some details are illustrated for stripline tuners, especially for the Low-Energy- and Medium-Energy-Boosters (LEB and MEB) in the Supercollider injector scenario.

I. INTRODUCTION

The injector scenarios for very large proton accelerators or for kaon factories usually contain rapid-cycling booster synchrotrons in the 3-GeV to 11-GeV range /1,2/, followed by larger synchrotrons which operate either as main rings or as medium-energy boosters for successive ring accelerators. In general, the injection energy of a low-energy booster is limited to a relatively low value, either by a smaller existing machine /1/ or by the intention to save on costly linac energy /2/. These limitations on injection energy demand an uppermost performance of the rf acceleration system in the successive booster: very high acceleration voltages combined with rapid and precise cavity tuning over a wide frequency range. The frequency-tuning range is much less severe for medium-energy boosters. We have listed a few examples in table 1.

Matching the frequency of accelerating cavities to the increasing velocity of the proton beam is usually accomplished by varying the permeability of a certain number of ferrite cores placed inside coaxial quarter-wave or half-wave resonators, whereby two different methods are possible:
(a) use of NiZn ferrite which is magnetically biased in parallel direction with the rf magnetic field (classical example: FNAL booster /3/), and
(b) use of microwave garnet ferrite which is biased in perpendicular direction with respect to the rf magnetic field.
In method (a), the effective mu of the ferrite for rf tuning is given by the derivative dB/dH of the magnetization curve. In method (b) it is approximately equal to the ratio B/H.
Since method (b) leads to very low magnetic rf losses above the saturation field of the garnet ferrite, it has stimulated the design and development of high-Q accelerating cavities for extremely high gap voltages (up to and beyond 100 kV) /4-9/, and the industrial development of cavity tuners /10,11/.

II. ORIGIN OF DIFFICULTIES

A price has to be paid, however, for the advantage of reducing the rf losses by perpendicular biasing, namely:
(a) the required bias current and its variation become large compared to parallel biasing,
(b) a heavy iron yoke for the magnetic return flux of the bias field has to be added, and
(c) fast variations of the (large) bias currents cause eddy currents in the rf conductors which surround the ferrite stack, limiting the attainable tuning speed and tuning accuracy.
In order to elaborate on points (a) and (c) in some detail, the acceleration cycle for the SSC LEB is illustrated by Fig. 1.

Table 1. Various Booster RF Data.

Machine	SSC-LEB	TRIUMF-Booster	SSC-MEB	Fermilab-Main Ring
Energy Range (GeV)	0.6 - 11	0.45 - 3	11 - 200	8 - 150
Frequency Swing (MHz)	47.5 - 59.8	46.1 - 60.8	59.8 - 60	52.8 - 53
Peak RF Voltage (kV)	700	750	4000	3500
DC Beam Current (A)	max. 0.5 (*)	2.0 - 2.7	max. 0.5 (*)	max. 0.39
Machine Circumference (m)	540	215.7	3960	6283
Acceleration Time	50 ms	10 ms	3 s	1 s
Max. df/dt of RF	1 MHz/ms	3.5 MHz/ms	2.2 kHz/ms	4.4 kHz/ms
Transition Energy (GeV)	N/A	N/A	20	15
Flat Top (s)	none	none	1	3 - 4
Repetition Rate (Hz)	10	50	max. 0.125	max. 0.4

(*) in detector test mode

*Operated by the Universities Research Association under contract with the U.S. Department of Energy

The speed of frequency tuning reaches a maximum of about 1 MHz/ms. In order to translate tuning range and speed into bias current values we have sketched the magnetization curve of an yttrium iron garnet ferrite in Fig. 2. We add the measured tuning curve of the TRIUMF test cavity /6/, see Fig. 3.

The low-loss range of permeability begins somewhat below 4; tuning is usually extended to values as low as 1.2. This corresponds to H-values ranging from about 20 to 250 kA/m.

In order to analyze the required accuracy of biasing, we may look at the slope of the tuning curve near 48 MHz in Fig. 3. It is approximately 500 Ampere-turns per MHz, or 5 At for a tuning correction of 10 kHz. If 16 kHz is the 3-db bandwidth

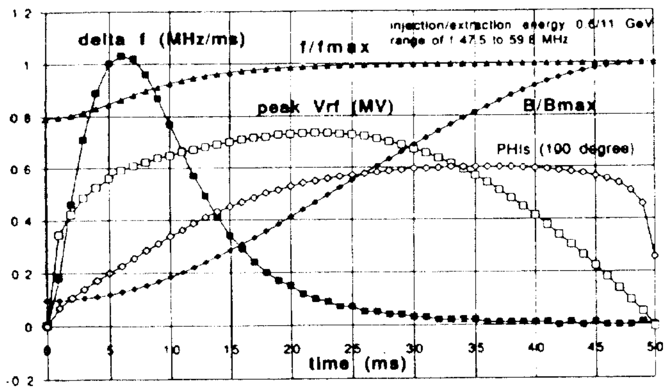

Fig. 1. Typical acceleration cycle of the SSC LEB. Frequency change, peak rf voltage, synchronous phase, and B/Bmax vs time.

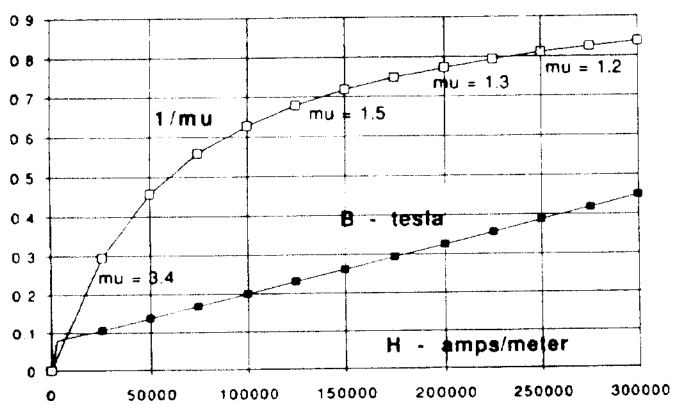

Fig. 2. Magnetization curve B vs H of an yttrium-iron garnet ferrite, and resulting effective permeability mu for perpendicular biasing (Trans Tech G 810).

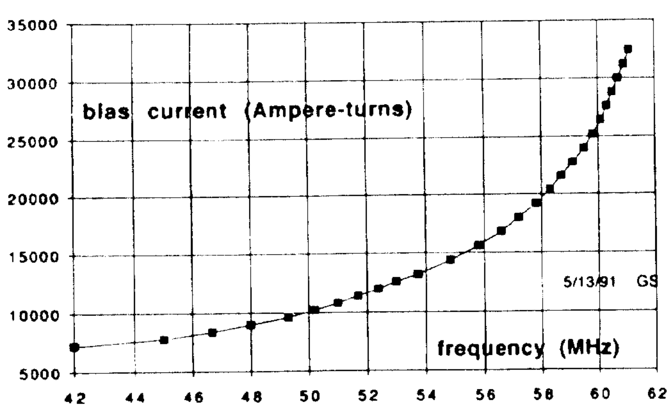

Fig. 3. Tuning curve for the TRIUMF test cavity /6/.

of the resonator (assuming Qo of about 3000), a tuning correction of 10 degree requires a bias change of 0.9 At. Related to the maximum bias current of 30000 At at 60.8 MHz, this would mean a bias control resolution of 3 10^-5.

The Fourier spectrum of a smooth bias current pulse for the SSC LEB contains frequency components up to about 50 Hz. A bandwidth of 300 Hz is desired for medium-fast corrections.

The requirements for wide, fast and accurate frequency tuning of a low-energy booster rf system are very difficult to fulfil. This is the penalty to pay for low injection energy and high beam intensity in the injector scenario.

III. EDDY CURRENT REDUCTION

The issue of eddy currents in the metallic envelope of the ferrite tuner is not necessarily eliminated by using thin sheet of metal and metal of poor conductivity. Peak rf gap voltage and speed of frequency tuning set limits. Slotted envelopes will help in most cases but will radiate a certain (again restricted) amount of rf power into the environment.

With great effort, eddy-current heating was reduced on the TRIUMF test cavity to acceptable temperatures /6/.

R. Smythe (University of Colorado) proposes an advanced "on-axis" tuner design with low eddy currents and fast frequency response /8/. He investigates single-gap cavities.

With few changes, his tuner can also be used as "off-axis" (=lateral) tuner on double-gap cavities, e.g., for drift-tube cavities investigarted by the author in /7/ and /9/. The cross-section of the tuner will change from concentric ring-shape to flat rectangular shape, and the beam pipe inside the tuner will be eliminated. The center of the cavity will look as sketched in Fig. 4 (cross-section with the beam tube in the middle). The bias field is oriented lengthwise in a ferrite layer rather than perpendicular to it /8/. The rf conductors will be slotted.

IV. ALTERNATING POLARITY BIASING

A different method to reduce eddy currents on perpendicularly biased ferrite tuners is alternating polarity biasing (APB).

The tuner will be divided into two (or more) successive or parallel sections which are magnetically biased in opposite directions. The result is a cancellation of the total induced voltage on the tuner circumference, and a reduction of the individual areas exposed to eddy currents. This is illustrated by a few sketches (Figs. 5-7).

Fig. 5 shows the cross-section of a ferrite-loaded stripline. which has a split innner conductor with magnetic biasing in opposite directions. The area at the center is an untuned fraction. This tuner could even operate without central connection A split-line version could be of interest for cavities working in push-pull mode, e.g. for the rf cavities of the SSC MEB. The inner conductors would then be loop-coupled to the cavity. In this case, no short-circuit connection to the outer conductor at the end is needed, only between the two inner ones.

Fig. 6 illustrates a subdivision into two successive tuner sections. The ferrite-filling factor may decrease in the second section to take the increasing electric field into account.

Finally, we also show an example of a pillbox-type ferrite tuner in Fig. 7. The tuner is incorporated into a compact folded quarter wave cavity /9/.

With APB, there will be no return yoke around the outer conductor of the tuner. Simplicity of magnet shapes and savings on magnet weight are additional advantages. We also refer to work done (with Ni Zn tuners) at INP Novosibirsk /12/.

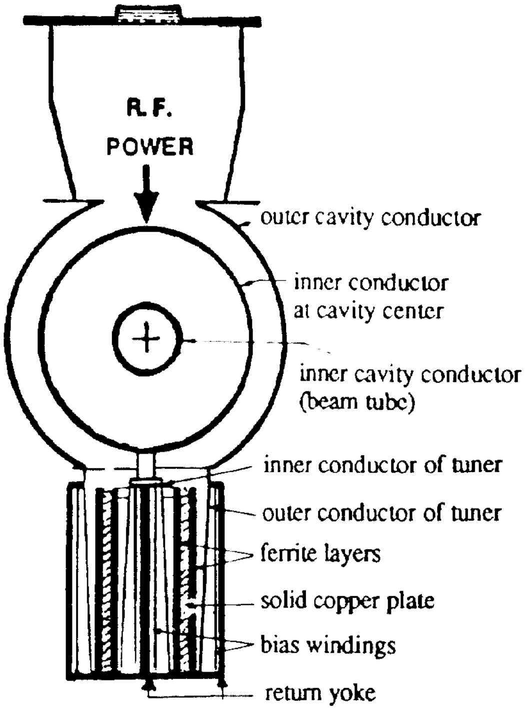

Fig. 4. Drift tube cavity /9/ with improved tripline tuner derived from /8/. Cross-section at cavity center

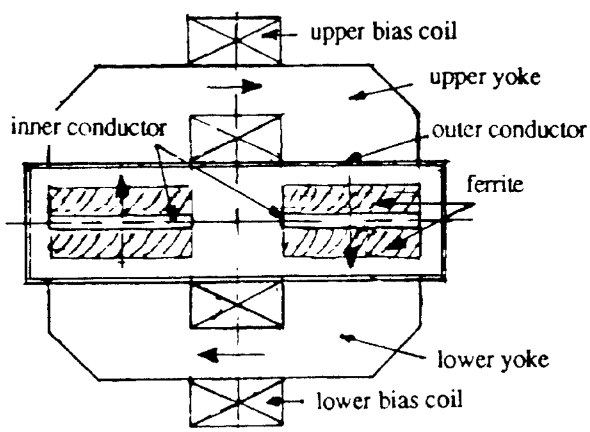

Fig. 5. Alternating polarity biasing (APB) of a ferrite-loaded stripline. The inner conductor is divided along the axis.

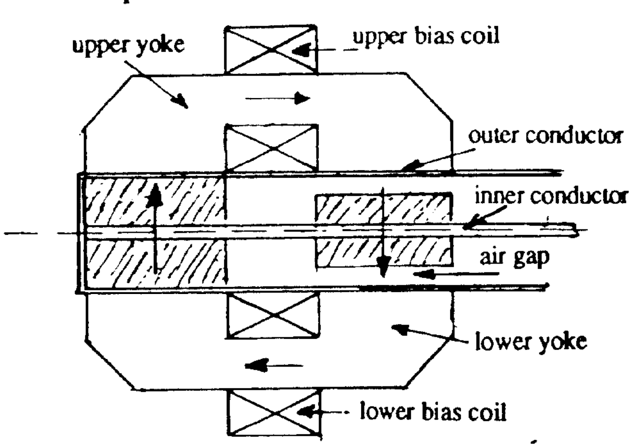

Fig. 6. APB of a ferrite-loaded stripline, version II. The line consists of two successive sections.

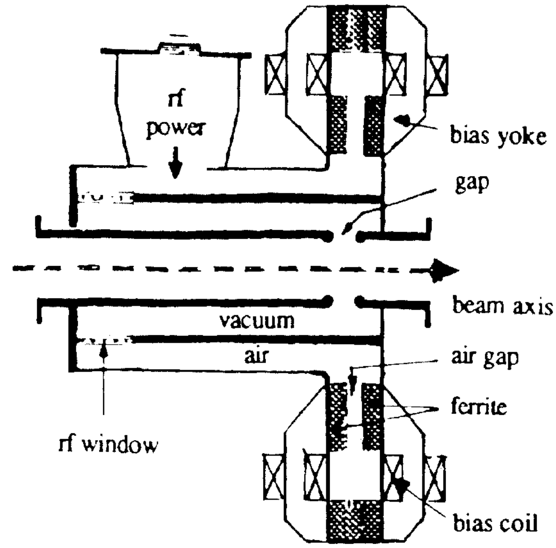

Fig. 7 APB pillbox tuner and folded LEB cavity /9/.

V. CONCLUSIONS

The proposed alternating polarity biasing (APB) scheme opens up new possibilities for designing ferrite tuners with lower eddy currents and faster frequency response. It offers great flexibility and simplicity for application to various booster cavities. Proven ferrite cooling methods are applicable.

VI. REFERENCES

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