New Design Concepts for Ferrite-Tuned Low-Energy-Booster Cavities

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Abstract

The design concepts for ferrite-tuned accelerating cavities discussed in this paper differ from conventional solutions using thick ferrite toroids for frequency tuning. Instead, tuners consisting of an array of ferrite-loaded striplines are investigated. These promise more efficient cooling and higher operational reliability. Layout examples for the SSC-LEB rf system are presented (tuning range 47.5 to 59.8 MHz, repetition frequency 10 Hz).

I. INTRODUCTION

Scenarios of very large proton accelerators and of medium-energy machines for very-high beam intensities usually contain rapid cycling booster synchrotrons in their injector chains in order to save on costly linac energy or to make use of existing circular accelerators of high intensity but limited energy.

The savings on the one side challenge an uppermost performance of the rf acceleration system in the follow-up machine: very high acceleration voltages combined with rapid frequency tuning over a wide frequency range. The rf system of the FNAL booster and its upgrade /1/ is our classical example. 18 ferrite-tuned double-gap cavities produce about 1 MV total rf voltage, tuned in frequency from 30 to 53 MHz, and operating with 15-Hz pulse trains. The 10-GeV Fermilab booster synchrotron is the only one of its kind in operation.

Studies and proposals of accelerators for kaon factories /2-4/ included boosters with a 32 to 11 % frequency swing in the 45 to 60 MHz range and repetition rates between 60 and 25 Hz.

A similar booster (LEB) but for lower intensity and 10 Hz repetition rate is included in the SSC injector scenario /5/.

Tables 1a and 1b contain the main parameters of the rf systems of some of these booster synchrotrons.

II. ORIGIN OF DIFFICULTIES

The cavity reference design for the low-energy boosters of TRIUMF and SSC is the quarter-wave cavity developed at Los Alamos (1984-87). It is shown in Fig. 1.

The use of low-loss microwave ferrites and application of bias fields perpendicular to the magnetic rf fields made it possible to achieve much higher Q-values compared to cavities using NiZn-ferrites (Fermilab-booster). This has stimulated a considerable increase of gap voltages (up to and beyond 100 kV). Magnetic and dielectric losses were seen as limiting factors in the layout of booster (and main ring) rf systems /2,3,5-8/. Mean power densities of about 0.2 W/ccm were considered to be the maximum values for stable operation /2/.

Besides power and cooling limitations, however, another limiting factor has to be taken into account: Partial discharge (corona) between ferrite cores of the tuner /9/. Due to the high dielectric constant of the microwave ferrite (relative epsilon about 14), the electric fieldstrength in small air gaps between ferrite cores is magnified by their relative dielectric constant.

Taking Ed= 25 kV/cm as breakdown field in air, for example, a stack of six ferrite cores with a total height of about 15 cm would begin to show partial discharge beyond a voltage of about 27 kV. The insertion of five layers of beryllia plates for cooling purposes raises this limit to about 39 kV.

Table 1a. Comparison of Various Booster Cavity Data.

Machine	SSC-LEB	TRIUMF-Booster	EHF-Booster	Fermilab-Booster
Energy Range (GeV)	0.6 - 11	0.45 - 3	1.2 - 9	0.2 - 10
Frequency Swing (MHz)	47.5 - 59.8	46.1 - 60.8	50.5 - 56	30.3 - 53.2
Peak Gap Voltage (kV)	88 / 117 normal/extended op.	max. 62.5 / 75 normal/extended op.	2 x 36	2 x 30
DC Beam Current (A)	max. 0.5	2.0 - 2.7	max. 2.55	max. 0.39
Cavity Length (m)	~1.25	~1.23	~3.25	~2.4
RF Input Power / Cavity (kW)	77 / 119	22.5 - 93	100 - 300	100 - 160
Tuning Speed	50 ms (10 Hz)	10 ms (50 Hz)	20 ms (25 Hz)	67 ms (15 Hz)

Table 1b.. Total RF Structure Length vs. Machine Circumference.

Number of RF Cavities	8 (single gap)	12 (single gap)	14 (double gap)	18 (double gap)
Total Length, all cavities (m)	~10	~15	~45.5	~43.2
Machine Circumference (m)	540 m	215.7 m	480 m	471 m
Fraction RF, approx. (%)	~1.85	~6.8	~9.5	~9.2

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

The onset of partial discharge may not easily be realized. High reliability in operation can be assured if the cavity is successfully tested with 50 % overvoltage, and if the components withstand a rise in temperature of 65 degree C.

High-power tests with cavities constructed according to /6/ and /8/ have shown that imperfect discharges and insufficient cooling will actually limit the operation of a ferrite-tuned cavity to a low fraction of the design voltage.

In the following, we will concentrate on possible improvements in both voltage holding and average power handling.

III. BENEFITS OF AIRGAPS

The insertion of airgaps between ferrite cores offers two beneficial effects: the breakdown voltage of the ferrite stack rises rapidly with increasing gap height, and the dielectric losses fall dramatically. In fact, they become negligible.

This is illustrated by Fig. 2. For a ferrite stack as shown in Fig. 1, the replacement of 6-mm beryllia disks by airgaps leads to a breakdown voltage of about 102 kV which would solve the voltage problem. Beryllia (or alumina) spacers could be used on the periphery of the ferrite cores where the electric field is low.

IV. AIRCOOLING

For modest average power losses in the ferrite tuner, aircooling may be applied as the most reliable cooling method. With a tuner structure as described above, longitudinal flow of air with strong turbulence around the inner edges of the cores would be most efficient. If we extrapolate experience with aircooled anodes of high-power electron tubes, it appears that average power losses up to about 10 kW.can be handled.

V. NUMBER OF CAVITY UNITS

Since the requirement of reliability overrides other design factors for the SSC low-energy booster, sufficient space for cavities is important. Table 1 shows that the LEB reference design deviates by far from comparable booster designs as to the ratio total rf-structure length to machine circumference.

VI. EDDY CURRENT EFFECTS

The outer conductor of the ferrite tuner will be slotted in order to allow AC components of the bias field to penetrate into the ferrite. It was difficult to develop an adequate solution

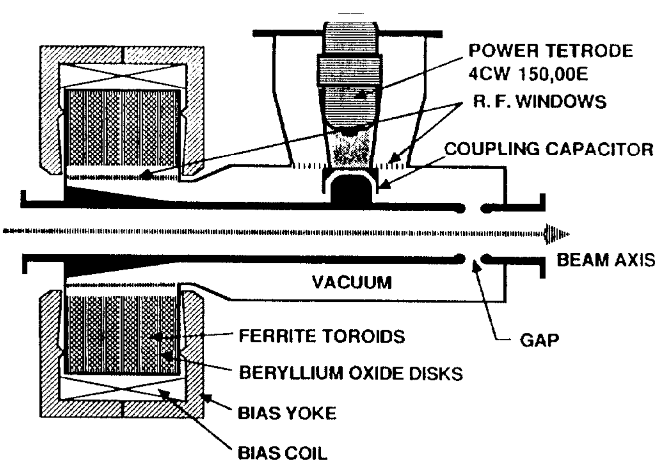

Fig. 1. Ferrite-tuned quarter-wave cavity designed by LANL, chosen as reference design for TRIUMF and SSC.

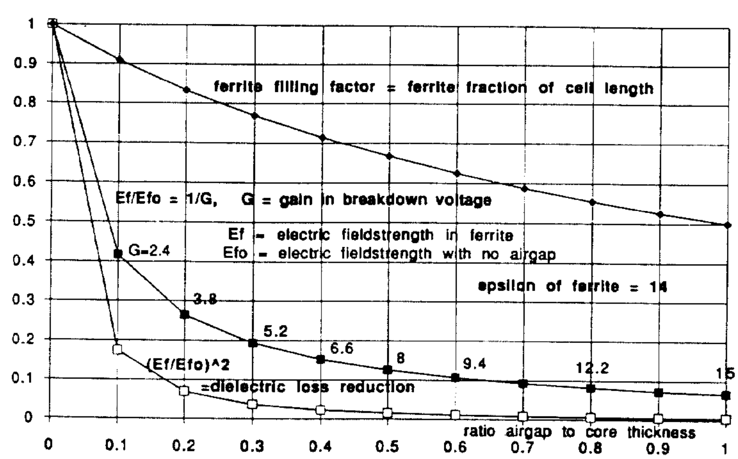

Fig. 2. Effect of airgap: gain in breakdown voltage, and reduction of dielectric ferrite losses.

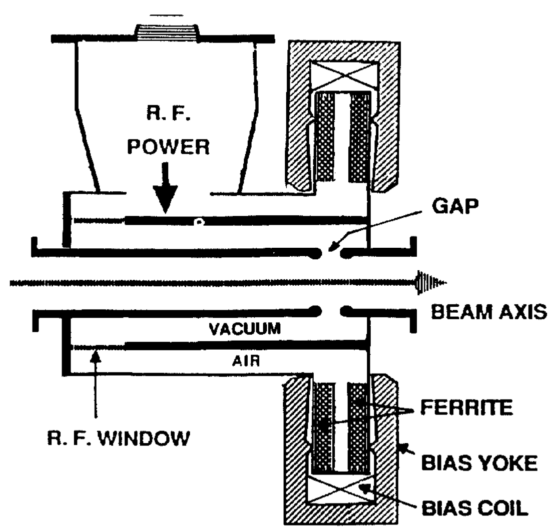

Fig. 3. Folded quarter-wave cavity with pillbox-type tuner

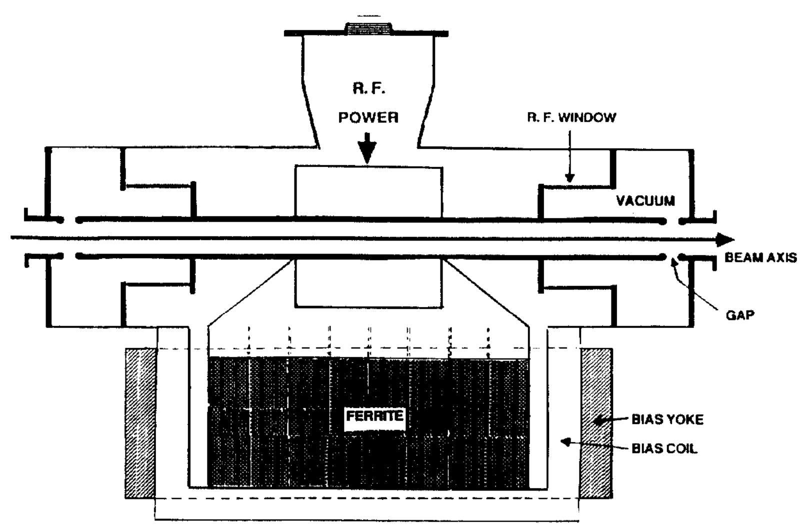

Fig. 4. Drift-tube resonator with lateral stripline tuner.

for the TRIUMF booster (50 Hz) but a satisfying design was found /10/. For the SSC-LEB (10 Hz), eddy current losses play a less important role (reduction by the square of the frequency). However, the penetration of higher harmonics of the bias field still needs attention. Five ms after the beginning of the acceleration cycle, the rate of rf frequency change reaches its maximum of 1 MHz per ms.

VII. FOLDED QUARTER WAVE CAVITY

A more compact cavity design compared to Fig. 1 is shown by Fig. 3. This is a folded quarter wave cavity. It may become attractive for the SSC LEB which requires somewhat less frequency tuning compared to the TRIUMF booster. Note that there will be only one rf window instead of two in Fig. 1.

VIII. HOM DAMPING

It is intended to use the type of HOM damper designed by W. R. Smythe /11/ which can easily be incorporated in any cavity type at the accelerating gap(s).

IX. STRIPLINE TUNERS

The idea of using ferrite-loaded striplines for cavity tuning has been promoted by E. Pivit /12, 13/. Commercial experience exists with a fast ferrite tuner built for the BNL light source /12/. This 20-ohm stripline tuner can handle a maximum dissipated power of 22 kW, max. 505 A and 25.2 kV. The outer conductor of the stripline is of rectangular shape (about 20 cm x 6 cm), the watercooled inner conductor carries ferrite tiles of about 6 mm thickness which are glued onto it with a very thin layer of epoxy resin.

The same technique has been successfully used over several decades in high-power ferrite circulators (in use with e+e- colliders at CERN, DESY and elsewhere for transmission of CW rf power up to 1.1 MW). The cooling capability is of the order of 10 W/ccm. Recent tests with even 20 W/ccm at CERN (324 MHz) did not lead to damages /14/.

Radiation damage tests with thermosetting resins are documented by CERN /15/. Results are shown for absorbed doses up to 100 MGy. It may be concluded that radiation damage will not be a major issue if stripline tuners of the kind described above will be used for booster rf systems.

A double-gap cavity with a broad stripline tuner designed for the possible use in the SSC low-energy booster is sketched in Fig. 4. The width of the inner stripline conductor is 100 cm. The distance between ferrite carriers is 5 cm; the airgap between the 12.5 mm thick ferrite layers is 2.5 cm. The length of the tuner is 40 cm. Tuning from 47.5 to 59.8 MHz requires a permeability tuning from 3.5 to 1.4.

The 4 layers of the tuner have a total surface of 1.6 qm. If 2.5 W/ccm are taken as conservative limit for mean losses we would obtain a value of 40 kW for the tolerable total losses.

With a breakdown fieldstrength of 25 kV/cm in air, the breakdown voltage of this tuner would be around 60 kV.

The voltage stepup ratios from the center of the (150 degree) drift tube to the gaps are 1.6 (47.5 MHz) and 2.3 (59.8 MHz).

The gap voltages of this resonator are limited to about 2 x 50 kV by the cylindrical vacuum windows between inner and outer drift tube conductors. The recommended operational gap voltages are 2 x 35 kV. Thus, 10 cavities would be needed to generate the required 700 kV total rf voltage for the booster.

Stripline-type tuners may also be designed in coaxial or pillbox shape, see for instance Fig. 3 or proposals in /13/.

X. CONCLUSIONS

A variety of options discussed in this report permit substantial improvements on both voltage holding capabilities and tolerable rf power levels of ferrite-tuned cavities for rapid-cycling booster synchrotrons.

XI. ACKNOWLEDGEMENTS

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