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FERRITE-TUNER DEVELOPMENT FOR 80 MHz SINGLE-CELL RF-CAVITY USING ORTHOGONALLY BIASED GARNETS

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Abstract

In the frame of the LHC Injector Upgrade program involving the existing 80 MHz cavities in the CERN PS accelerator, an orthogonally biased ferrite tuner is foreseen to complement the current motor-driven piston tuner. This ferrite tuner shall provide the possibility of a fast frequency shift of about 200 kHz on the fundamental mode, to allow a fast switching between proton and ion frequencies. In order to avoid water cooling and related issues, the challenge was to bring magnetic losses in the tuner to a minimum such that a forced air cooling scheme will be sufficient. The tuner was first designed with simulation tools, a prototype was built and low-power RF testing was performed on the tuner-cavity combination to evaluate tuning range, bandwidth, and stability. These tests were carried out on a single-cell copper RF cavity mock-up with a resonance frequency of 88 MHz, where the ferrite tuner is connected via a tuning loop and the perpendicular magnetic bias for the ferrite tuner is provided by a DC bias supply. Simulations and test data will be presented.

INTRODUCTION

For the acceleration of protons and ions, the CERN PS accelerator makes use of three single-cell RF-cavities with a resonance frequency of 80 MHz [1]. These existing cavities are currently equipped with piston tuners for frequency shifts to allow the acceleration of protons and ions. We developed a ferrite tuner with the intention to complement the motor-driven piston tuner and to provide a fast frequency shift of about 200 kHz on the fundamental mode. Consequently, we aimed for a design that provides a maximum frequency range that should be reached with a minimum change of biasing field while keeping the ferrite material sufficiently magnetized such that the material stays entirely in the low loss state during operation.

TUNER DESIGN

The tuner consists of a coaxial structure terminated with a shortened plug. The space between inner and outer conductor is partly filled with the low-loss tuneable ferrite garnet G-510 [2] and the tuner is inserted into a toroidal coil set-up that provides orthogonally magnetic biasing fields, i.e. the bias field is oriented perpendicular to the magnetic RF-field. The actual tuning is achieved by making use of the fact that the relative permeability of ferrites can be changed if a magnetic bias field (static or slowly varying) is applied to the material. In a first step, a design was carried out by means of simulations in HFSS. Figure 1 (left) shows a sketch of the ferrite-filled tuner with the biasing coils connected in series, and the HFSS model including the coupling loop that indicates the connecting plane to the cavity (right). It should be noted that the simulations have been carried out on the geometry of the 80 MHz cavity, for which also the final tuner design is intended.

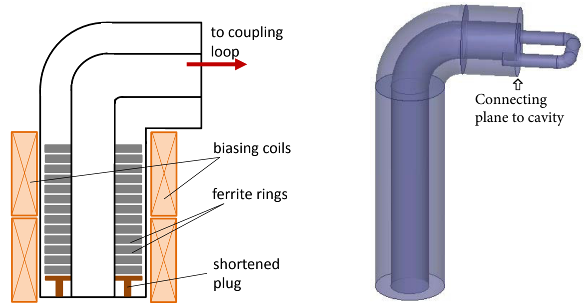

Figure 1: Left: Sketch of coaxial ferrite-filled tuner with bias coils; Right: HFSS model of tuner with coupling loop.

Due to availability, however, measurements were carried out on an 88 MHz mock-up cavity structure. Figure 2 shows a picture of the set-up with which a tuning range of ± 100 kHz around the resonant frequency f_{res} is pursued.

Figure 2: Picture of the mock-up 88 MHz cavity used for testing of the tuning-concept with the fast ferrite tuner.

The tuner design was constrained by a fixed ferrite ring size in order to make use of rings being available from a former application, and one of the existing access ports to the cavity had to be used due to local space restrictions. As a consequence, the tuner's coupling strength is limited due to its location, however, as we could show from our

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measurements, the obtained coupling strength is sufficient for this application.

SIMULATION OF THE GEOMETRY

The entire measurement set-up was simulated in Ansys-HFSS. For the simulation of the tuner, a precise modelling of the ferrite material is required, i.e. complex material parameters ε_r, μ_r vs. frequency and as a function of the magnetic bias were needed for input. This data was obtained from direct measurements on the ferrite rings [3].

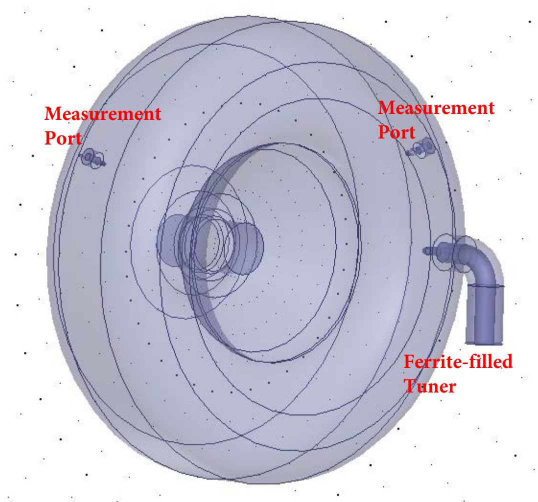

Figure 3: 3D Ansys-HFSS model of the 80 MHz cavity with tuner and measurement ports.

Figure 3 shows the Ansys HFSS model of the 80 MHz cavity with tuner mounted and the two measurement ports used to simulate transmission measurements. The tuner (as shown) consists of a coaxial line of about 90 cm total length, including the flange geometry and the coaxial elbow. It is filled with a densely packed stack of ferrite rings and connected to the cavity's geometry via a coupling loop. The cavity has an outer diameter slightly above 2 m. In an first step, we carried out independent simulations of the tuner geometry and the cavity in stand-alone mode. The complex reflection factor in the connecting plane tuner-to-cavity was calculated and an inductive load representing the coupling loop in the connecting plane was added. This way, we obtained a narrow-band matching around the resonance frequency which is sufficient to reach a frequency change of ± 100 kHz. For the acceleration of protons and ions, merely two defined positions are needed instead of the full tuning range. This allowed us to maximize tuning range by operating around the *Open* position in the Smith-chart in the tuner plane, making use of the operating point where maximum inductance respectively the minimum capacitance can be reached while keeping the ferrite in its low-loss state close to saturation. For the cavity with the empty tuner mounted, we calculated a resonant frequency f_{res}=81.9 MHz, i.e. the desired tuning range is 81.8-82.0 MHz. Fig. 4 (top) shows the simulation of the 80 MHz cavity with magnetic biasing applied that puts the resonance frequency of the cavity through the *Open* position of the Smith-chart by a changing the relative permeability in the ferrite garnet.

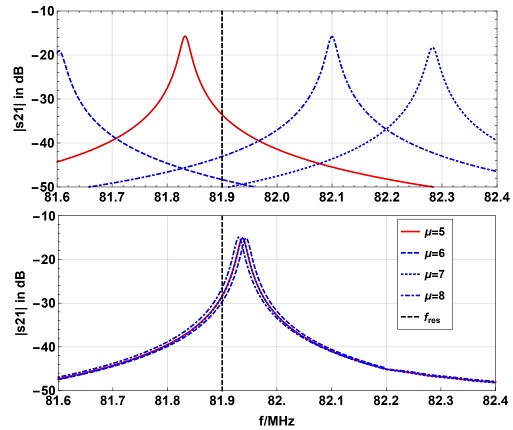

Figure 4: Simulation of the 80 MHz cavity with the magnetic bias system. Top: with tuning the cavity through the *Open* position in the tuner plane; Bottom: weak cavity tuning due to an inefficient operating point.

MEASUREMENT SET-UP

A tuner prototype was built and low-power RF testing was performed on the tuner-cavity combination to evaluate tuning range, bandwidth, stability, and loss behaviour. As already mentioned, these tests are carried out on a single-cell copper RF cavity with a resonance frequency of about 88 MHz, where the ferrite tuner is connected via a coupling loop and the perpendicular magnetic bias for the ferrite tuner is provided by a DC bias supply. In a first step, we determined the required length of the coaxial tuner. This calculation can be carried out in a good approximation without fixing the exact amount of ferrite in the line, since each shorted line is always reactive and its input impedance at the connecting port (inductive or capacitive) is depending on the line length. Thus, we filled the line with all 18 available ferrite rings with ID=70 mm, OD=127 mm, and 12.7 mm thickness, each.

Tuner Length Determination and Coupling Loop

The importance of the correct determination of the line length could be demonstrated by measuring a tuning range with bias currents from 0-400 A in an inefficient operating point. When we fixed the moveable shortened plug to the lowest possible position, almost no tuning effect could be obtained. Confirmed by simulaton (see Fig. 4, (bottom)), we measured about +2.3 kHz shift on the resonant frequency for a total tuner length of about 120 cm. The measurements also showed that for a further increase of the tuning range, the coupling loop had to be adjusted in orientation and size to increase the area penetrated by magnetic field lines. Figure 5 (right) shows that a change of coupling strength can be obtained without significant change of the working point in the Smith-chart (change from blue line (continuous) to red line (dashed)). In addition, it can be seen that a change of coupling strength is possible beyond matching point (over-coupled) indicating that the desired tuning range around the

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Open position in the Smith-chart will be possible, where a maximum tuning can be obtained with a minimum change of bias current. In this position, it will also be possible to carry out a de-Qing of the cavity to values below 100 by adjusting an appropriate input current on the bias system, i.e. without carrying out any hardware changes. A cavity de-Qing gives the possibility of operation scenarios [4] without the need of by-passing the cavity.

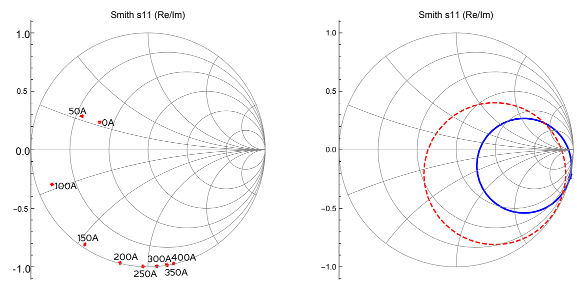

Figure 5: Left: Tuning range obtained with trombone; Right: Couplings obtained by changing the active area in the coupling loop without significantly moving the operation point.

The test for the tuner length was possible since the coaxial line was deliberately constructed longer than what is required in the final design and a moveable shortened plug was inserted between the inner and outer conductor. We did this for various purposes: firstly, the diameter of the shortened lid of the coaxial line is too large to allow its insertion into the biasing coils. Hence, a shortened plug was put *into* the line (see Fig. 1, left) such that it can be fixed in any position along the line allowing for an adjustment of the total tuner length. In addition, the shortened plug allows to lift the stack of ferrite rings into the area of homogeneous distribution of the magnetic bias field, thus avoiding coil-end-effects. Finally, since a considerable amount of reactive power will have to be shifted via the tuner, a forced air cooling might be required to avoid heating up of the ferrites and associated temperature drifts. In that case, we will put teflon washers between the ferrite rings to provide a spacing that allows forced air flow. This will, of course, increase the line length.

Next, we experimentally confirmed the calculated input impedance of the ferrite-filled coaxial line. Fig. 5 (left) shows measurements of S_{11} taken on the tuner in stand-alone (not connected to the cavity). By means of an adaptor piece, we connected a moveable coaxial trombone, and we set the working point to position (0-1j) in the Smith-chart (roughly 6 o'clock). Then, we changed the tuning current from 0-400 A. This showed two effects in the Smith-chart: firstly, the length of the trombone worked according to our predictions by moving the operating point to (0-1j). Further, for values of biasing current higher than approx. 100 A, the ferrite reaches its saturation magnetization where magnetic losses are greatly reduced and the actual tuning takes place on the outer contour of the Smith-chart **in the tuner plane**. For the sake of completeness, we also show two positions taken at very low current (0 A and 50 A), where the ferrite losses cause the operating points to move towards the center of the Smith-chart and into the inductive plane.

Transmission Measurement

In a next step, transmission measurements of the cavity were carried out by means of two small measurement ports with coupling loops. As a reference value, we define the resonance frequency of the cavity with the ferrite tuner mounted, but without powering of the magnetic bias system. This way, a resonance frequency f_{res} = 87.9555 MHz and an unloaded Q_u=18500 is reached. The available ferrite has a saturation magnetization ($4\pi M_s$) of about 550 Gauss which can be reached with about 100 A of biasing current in the coil. Therefore, in order to obtain the desired tuning range, biasing currents in the range of 0-300 A are considered largely sufficient and a power supply that provides up to 400 A was chosen. From simulations, the total length of the tuner should be about 90 cm, including the coaxial elbow and a ferrite stack of 18 rings, densely packed. Therefore, we lifted the shortened plug by 30 cm and measured with different bias currents.

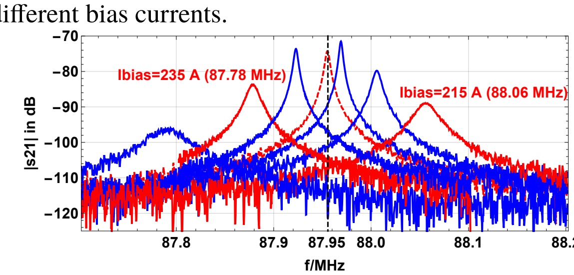

Figure 6: Measurement of tuning range obtained on the 88 MHz mock-up cavity for different bias currents.

Figure 6 shows that the desired tuning range could be reached with biasing currents of 215 A (f_{res}=88.06 MHz), resp. 235 A (f_{res}=87.78 MHz). The dashed line depicts the resonance frequency of the cavity with the tuner mounted, but without magnetic biasing (f_{res}=87.95 MHz).

CONCLUSIONS

A prototype for an orthogonally biased ferrite tuner was built and could be implemented by means of a toroidal coil into which a ferrite-filled shorted coaxial line was inserted. From measurements we could show that a frequency tuning of the desired range of ± 100kHz can be reached without a significant reduction of the Q-value of the cavity. Since not the entire tuning range will be needed for cavity operation, a solution could be used that implies to pass the *Open* point in the Smith-chart while tuning from one resonant frequency to the other. This allows the use of reasonably low tuning currents, i.e. the bias system remains moderate. Furthermore, this feature can also be used to carry out a de-Qing of the cavity to values below 100 by feeding an appropriate input current on the bias system that tunes into the *Open* point on the Smith-chart for the tuner plane.

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