RF cavity for the IOTA ring at FAST

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September 23rd 2016

Abstract

Fermilab is currently constructing a superconducting electron linear accelerator at Fermilab Accelerator Science and Technology Facility (FAST) with the aim of conducting a broad range of beam experiments for the improvement of the current accelerator technology. One of the unique features of FAST is the presence of a storage ring for both protons and electrons capable of permitting ring-based beam dynamics experiments. Since the Beam Position Monitor (BPM) for detection of particles needs bunched beams and since it is necessary to combat the loss of energy of electrons, a RF cavity is being assembled and tested. In this paper we describe the work done to ensure the impedance matching and the resonance condition with the purpose of optimizing the transfer of energy from the RF voltage supply.

1. Introduction

The Integrable Optics Test Accelerator (IOTA) ring will be one of the experimental areas of FAST. It is currently under construction and will serve as a storage ring for both protons and electrons once completed. It should permit ring-based beam dynamics experiments with objectives concerning: the possibility of using integrable optics with non linear magnets and electron lenses; techniques for space-charge compensation; optical stochastic cooling; exploration of the nature of the quantum wavefunction of a single electron. In particular it should be capable of circulating 2.5 MeV proton beams and 150 MeV electron beams[1].

A radio frequency (RF) cavity is going to be used for the bunching and modulation of proton and electron beams travelling along the ring; this operation is demanded by the BPM system. It is also strictly needed in case of electron beams because without energy compensations electrons would lose energy due to synchrotron radiation and would be lost in the ring after about a thousand revolutions. A former work[2] demonstrated that a good choice for the bunching frequency is 30.62 MHz. The cavity under completion is capable of bunching the electron beam at that frequency whereas the same task cannot be accomplished for the proton beam. This is the reason why it was decided to bunch protons at 2.19 MHz first and then to modulate the bunches at the required frequency of 30.62 MHz. In both cases the harmonic number is h=4.

Two major problems related to the assembling and control of the cavity are the impedance matching and the resonance between current and voltage. Regarding the former, it is known that the transmission line impedance and the load impedance of an electrical circuit need to be equal for the energy to be transmitted from the source to the load and not reflected back (see for example [3]). On the other hand, the feeding voltage and current should be in phase if one wishes to deliver the maximum power to the cavity. Both conditions are mandatory for the optimum transfer of energy to the cavity. In this paper we describe how we deal with both problems, in particular we focus on the test of the system designated and already designed to achieve and maintain the

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resonance condition. Here our goals follow: verify that it is possible to achieve a steady state accuracy of the phase no greater than ±0.5˚ by means of the resonance control system; verify that the same system is able to recover the set point after a perturbation no greater than 40˚; ensure a SWR smaller than 1.2:1 (or equivalently power loss less than 0.8%). Regarding this last issue, it is worth mentioning the fact that during real operations an alarm system will be used to monitor the SWR: if the SWR becomes worse than 2.5:1 (18% of power loss), the RF amplifier will be shut down. The system was not activated because it was indeed our aim to test the cavity and improve the SWR.

2. Working conditions and experimental setup

2.1 The cavity and its electrical model

Only one RF cavity is used for both species of particles hence it is indeed a joint cavity made of two portions: a disk separator with good contacts with internal and external conductors provides the necessary separation between the two sides which operate at the two different frequencies. The cavity is in fact an aluminum pillbox hosting the beam pipe, with one ceramic gap for each side causing the bunching. In order to decrease the frequency of operation down to the required values and to increase the quality factor ferrite disks were inserted, 3 on the electron side and 8 on the proton side with magnetic permeability μ_r about 5 and 15 respectively[4]. Finally, cooling plates are set in between the ferrite disks to guarantee thermal stability and prevent the cavity from heating.

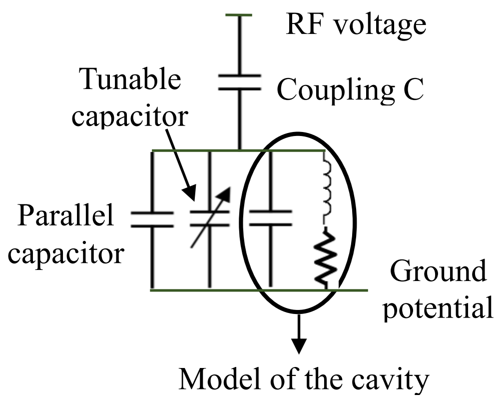

Fig. 1: The equivalent electrical model

For a better understanding of the electrical properties refer to Fig. 1 which shows how we can model each side of the cavity. It behaves basically as a RLC circuit where the inductive and capacitive components are mainly determined by the ferrite and the ceramic gap respectively. The resistor is associated to the resistivity of the path travelled by the current.

There are three additional capacitors. The one named "coupling" in part represents the capacitive contribution of the feeding line but mainly accounts for a capacitor which is going to be placed in between the feeding coaxial cable and the cavity because of the need for impedance matching. The parallel and tunable capacitors are both required for the tuning of the cavity: the former provides a gross modification of the resonance frequency whereas the latter is exploited for the precise refinement. They are both in parallel to the ceramic gap thus in principle they could have been replaced by just one capacitor; yet two distinct capacitors are used because only one variable capacitor could not have been mounted inside the cavity because of its large dimensions.

2.2 The tuning at 2.19 MHz

The feasibility of the tuning of the cavity at 2.19 MHz has been accomplished by means of the PID feedback loop and of the experimental setup described in [5]. As described there, the same resonance system had already been used for the tuning of the electron side at 30.62 MHz and proved to be

working correctly. As stated above, one of the objectives was indeed to perform a similar test for the proton side at 2.19 MHz. We kept the same reference point at 1˚ instead of using 0˚ for two reasons: undershoots and oscillations are visible (they could not be with 0˚ as nominal value because of the incapacity of the wattmeter to measure the sign of the phase); as the point of measure of the phase is not the feed point, there is a systematic error (phase offset) due to the length of the coaxial cable which can be accounted for in this way.
To perform the experiment all ferrite disks have been inserted in the cavity along with the copper plates in between them. The tunable capacitor has been connected in parallel to the gap and mechanically linked to the pulley system via a belt: it is composed of a stepper motor and a potentiometer. This is basically the same configuration which was used for the electron side[5]. The separator was placed in position and the pillbox cavity completed by accommodating the top part as well. The final beam pipe has not been added yet because of its extreme delicacy.

2.3 Impedance matching

The feeding of the cavity by the RF voltage supply and the RF amplifier is realized by means of a 50 Ω coaxial cable. As explained above one of our purposes was to ensure the impedance matching so to optimize the transfer of power. For this reason different capacitors and different configuration were tried at the feed point until the matching was achieved. We could know how good the matching was thanks to a LP-100A RF vector wattmeter which displayed the SWR. In the meantime, we tried to adjust the value of the parallel capacitor to have resonance as close as possible to the desired frequency 2.19 MHz, keeping in mind that the fine tuning had to be performed by means of the variable capacitor.

3. Results

For what concerns the impedance matching we found that a convenient value for the coupling capacitance is 17 pF. With the final capacitance values for this capacitor and the others (see below) we were able to achieve a SWR smaller than 1.1:1, hence below the prefixed upper limit.
Regarding the resonance, consider first that the ceramic gap's capacitance is 30 pF whereas the variable capacitance is some 30-50 pF. It was understood that a parallel capacitor of 400-600 pF could be a good possibility to force the resonance frequency to be close to 2.19 MHz. However, at the current status the best frequency which was obtained was about 2.45 MHz, which could not be significantly decreased farther by just increasing the capacitance, despite not being too far from 2.19 MHz. Thus it was noticed that relying on the capacitors only may not be sufficient for an approximate tuning. There is another reason for being careful about the increase of the capacitance: adding capacitors to lower the frequency would have the negative effect of reducing the quality factor. As the quality factor is the ratio of the stored energy to the energy loss in one cycle, effort is made in general to keep it at a high level.
Consequently an improvement of the cavity has been planned: an additional ferrite ring should be inserted to decrease the resonance frequency, which requires a minor modification of the separator to accommodate the new ferrite disk. Moreover, since the quality factor is proportional to the inductance the additional disk would help increasing it as well.
Despite the resonance frequency was a bit far from 2.19 MHz, it was planned to verify the efficacy of the resonance control system in catching the reference phase point. In fact, the tuning has to be

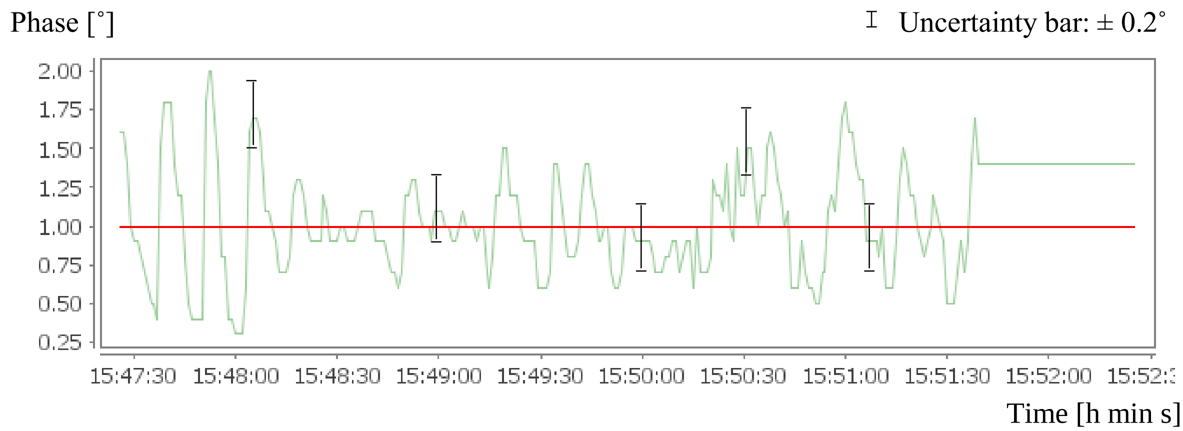

Fig. 2: The uncontrolled motion of the shaft produces undesired oscillations about the reference phase

working in any case: carrying out the modification proposed above would change the inductance and consequently the resonance frequency but not the efficiency of the tuning process.

Still another problem had to be faced before the test of the tuning could really be performed. During the first trial it was noticed that a strong noise was preventing the resonance control system from finely tuning the phase: the phase kept widely oscillating about the reference point, as can be seen in the graph of Fig. 2 (some oscillations are larger than half of a degree). The origin of the noise has been traced back to the electromechanical assembly which should control the rotation of the variable capacitor's shaft. As a matter of fact, the shaft is not sufficiently rigidly connected to the capacitor and room is left for undesired bending. Consequently the torque from the motor not only produced the desired rotation but also undesired movements of the shaft up and down. Obviously these slight deflections up and down are not tolerable if the correct and precise control of the cavity is demanded. Furthermore, in the long run the movement could be responsible for the damage of the capacitor. A solution has to be found for the final assembling, nevertheless it was managed to continue the test by removing the potentiometer from the pulley system (Fig. 3). Having a two-wheel pulley system instead of three proved to be quite satisfactory: deflections were now unperceivable. Note that as a result of this temporary configuration it was no longer possible to know the exact position of the stepper motor, yet it was not a problem because the tuning could still be performed. It was only necessary to be careful in that the rotation would not go too long a way in one direction or in the other because of the possible damage of the capacitor. In practice that was not a serious concern since once the cavity had been set up close to resonance the PID loop would produce only a tiny rotation of the stepper motor. In fact, close to resonance the required adjustment was rather small, in other words the error was already small enough to avoid large rotations.

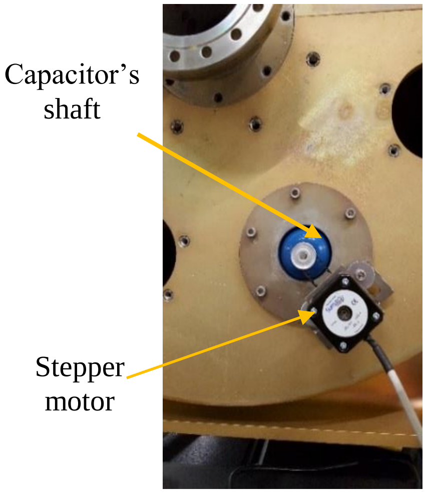

Fig. 3: The temporary arrangement

Before starting the PID tuning the program was allowed to run the auto-tuning[5]. It is a process by which, once the reference point is manually set, the program automatically looks for the best parameters (proportional, integral, derivative) to be used in the PID error-output formula. Then the new values were updated into the program datasheet. As a matter of fact during the test it was found by trial that slightly different values were able to provide a better response to perturbations:

Fig. 4: Top to bottom four plots recorded during the tuning of the cavity.1, 3 and 4 display the actual phase and the set point (phase in degrees vs. time [h min sec]); the uncertainty corresponds to ± 0. 2°in all cases. 2 shows the output of the loop computation (number of steps vs. time).

reduced overshoots and smaller oscillations about the set point (see below).
In Fig. 4 a series of plots taken during the tests are visible. Starting from the top, in the first two graphs one can observe the response of the system to a perturbation of about 6˚ which was produced by rapidly decreasing the feeding power from 15 W to 4 W. The first one shows the time evolution of the phase, the second one the number of steps ordered to the stepper motor by the PLC. After a few oscillations the set point is caught again and the phase settles in its very proximity for the rest of the time. Similarly, in the third picture (related to a previous perturbation resulting from increasing the power from 2 W to 15 W) very tiny oscillations are visible, at best of about 0.1˚ at steady state.
A minor problem came out during the test due to heating. Observe the last graph in Fig. 4. Though the phase is always quite close to the reference value, larger oscillations occur. It is our belief that these fluctuations are the response to some kind of noise, most likely the heating of the cavity. In fact, as the pattern appears to be stationary it seems that the system was not trying to chase the set point, which had already been reached, but rather to account for small variations of the properties of the cavity (impedance, capacitance and inductance). The variation was produced probably by heating due to ohmic losses and that is indeed the reason why cooling plates were inserted. The explanation is supported by two observations: a slow but steady growth of the cavity's impedance displayed by the wattmeter during the tuning; the stepper motor was constantly slowly moving in one direction only and not back and forth as it would have done in case of tuning. During normal operations this problem should not arise thanks to the cooling provided by the copper plates. In any case, a possible way of limiting the wiggles is to reduce the proportional gain of the PID formula so that the number of steps computed on the basis of the error is smaller.
Finally, the estimation of the cavity quality factor was performed in a very simple way. Recalling the equivalent formula for Q which involves the frequency, it was sufficient to measure the bandwidth of the response of the cavity in the nearby of the resonance frequency. This is easily accomplished by determining the two side frequencies at which the phase changes by ± 45˚ with respect to the zero phase at resonance. Several measured values were similar and always about 40. This is perfectly reasonable as typical values for ferrite loaded cavities are of the order 30-40 because Q is dominated by the ferrite.

4. Conclusions

For what concerns the impedance matching it was proved that it is possible to use a capacitor at the feed point to reach values of SWR better than the requirement 1.2:1. In particular a 17 pF capacitor could be a possible choice at the status of art of the cavity. However, if an additional ring is going to be placed on the proton side, new measurements should be carried out in order to check whether a different coupling capacitor is needed to match the line impedance with the new inductive component.
Regarding the resonance, it was demonstrated the effectiveness of the control system in tuning the phase also at ≈ 2.4 MHz. It is able to maintain the phase within few tenths of degrees from the reference value (including the uncertainty) and, in case of perturbations, to recover it after a few oscillations. In real working conditions perturbations much smaller than those intentionally induced during the test are expected (a few tenths of degrees), thus the settling time should be much shorter and also the number of overshoots should be limited.

The mechanical system required to apply the torque to the capacitor’s shaft is currently being redesigned; bearings are going to be used to improve the stability and forbid deflections.
After the insertion of the last disk, the assembling of the ultimate pulley system and the completion of new tests similar to those described above, the cavity is going to be completed with the final pieces and vacuum pumps will be installed.

References

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