RF cavity for the IOTA ring at FAST

Summer internship at Fermilab 2016
Italian Graduate Student Program

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1. Introduction

Fermilab is currently constructing a superconducting electron linear accelerator with the aim of conducting a broad range of beam experiments. The purpose is not to investigate the properties and behaviour of particles and to answer the fundamental questions of physics, rather the final goal is the establishment of a centre of excellence in beam theory and experiments. In particular FAST (Fermilab Accelerator Science and Technology Facility) should be used to study the limitations to beam intensity and to look for alternative solutions to beam generation, acceleration and manipulation as well as to describe and predict the behaviour of the existing and future accelerators; in other words the main subject of the project is accelerator physics. Thus the facility is intended for any interested user who wishes to carry out experiments concerning advanced accelerator research and development. FAST is supposed to be fully constructed by 2020, though the first trial beam should be launched next year.

The backbone of FAST is a RF photoinjector coupled with superconducting accelerating cryomodules (Fig. 1). The photocathode drive laser produces a train of bunches at 3 MHz within 1 ms duration macropulse, then the emitted electron bunches are accelerated by two SRF cavities to 50 MeV. The following beamline includes quadrupole and dipole magnets as well as a four bend chicane. In addition, a RFQ proton injector is going to be assembled in order to produce 2.5 MeV proton beams.

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. It is known as the IOTA, which stands for Integrable Optics Test Accelerator (Fig. 2). It is expected to serve as one of the experimental areas of FAST and its main goals concern: the possibility of using integrable optics with non linear magnets and electron lenses; techniques for space-charge compensation; optical stochastic cooling; even exploration of the nature of the quantum wavefunction of a single electron. The IOTA ring should be capable of circulating 2.5 MeV proton beams and 150 MeV electron beams. The following table summarizes some of the important parameters.

Nominal p^+ kinetic energy	2.5 MeV
Nominal p^+ beam intensity	8×10^{10}
Transverse p^+ emittance	1-2 μm
Nominal e^- beam energy	150 MeV
Nominal e^- beam intensity	1×10^{9}
Transverse e^- emittance	0.1 μm
Circumference	≈ 40 m

Tab. 1 Main parameters about the IOTA ring

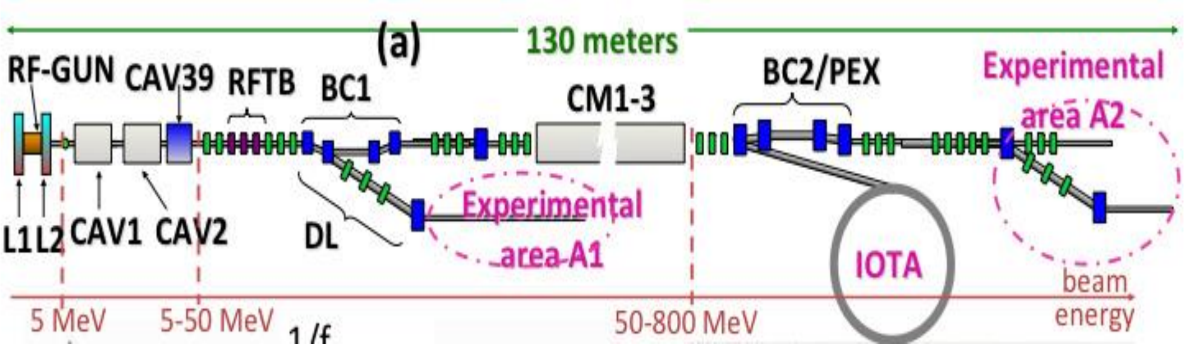

Fig. 1 Schematic of the ASTA/ IOTA facility

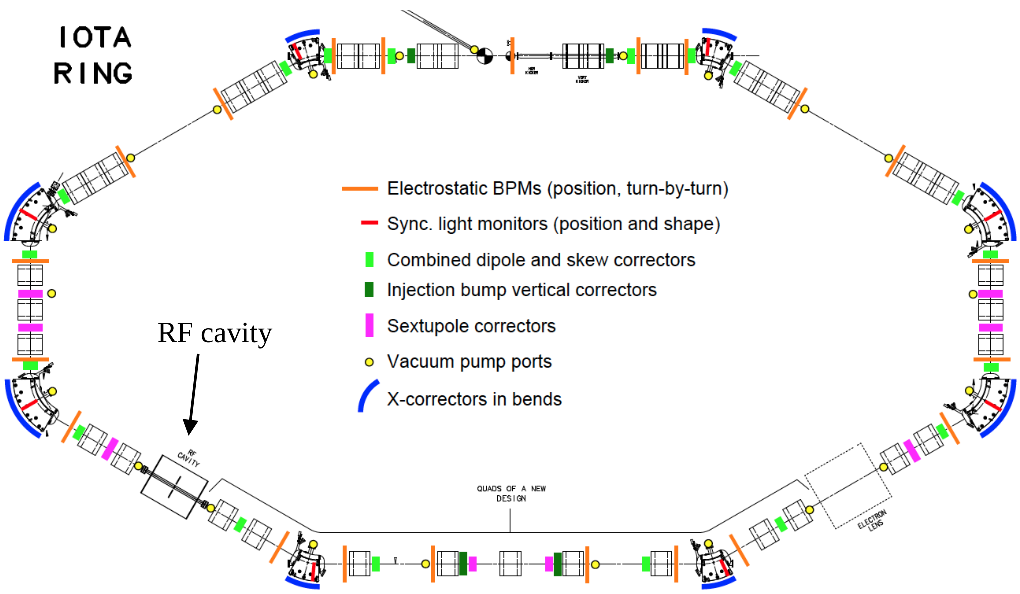

Fig. 2 Schematic of the IOTA ring currently under construction

2. The need for a RF cavity

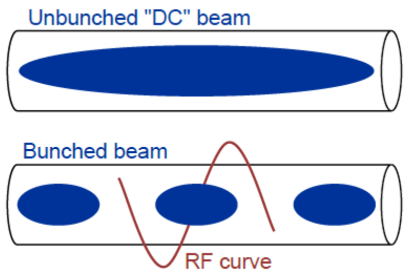

Fig. 3 Beam bunching due to RF phase focusing

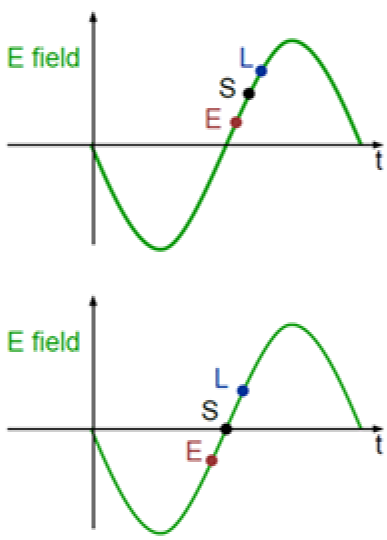

Fig. 4 Schematic of the phase focusing. Above the packet is accelerated on the whole, below it is not. L: late, E: earlier, S:

My work focused on the construction, characterization and tuning of a radio frequency (RF) cavity to be used for the bunching and modulation of proton and electron beams travelling along the ring. It means that the result of an initially continuous beam passing through the cavity several times is the formation of bunches, or packets, of particles, as depicted schematically in Fig. 3. The bunching is required because of the nature of the Beam Position Monitor system (BPM) which cannot work with continuous beam. However, the cavity is also strictly needed by the electron beam because without energy compensations electrons would lose energy due to synchrotron radiation and would be lost in the ring after about a thousand turns.

According to a previous simulation, 2.5 MeV protons are to be bunched approximately at 2.19 MHz and 500 V, 150 MeV electrons at about 30.62 MHz and 1000 V. In addition each proton packet undergoes modulation at 30.62 MHz so that an “internal pattern” appears. This is because the BPM system works correctly at approximately 30 MHz so that also protons need to be modulated at that frequency. Both tasks are accomplished by the time dependent electric field localized in two separated gaps contained in the same assembly and operated at different frequencies.

Since the harmonic number is h=4 (h=56 for the proton beam when being modulated) for electrons, they travel along the ring in a period 4 (56) times longer than the period of the varying field. The h number also tells the maximum number of bunches allowed in the ring. Thus, each time they reenter the cavity they are approximately in phase with the field. Actually, it is indeed the tiny discrepancy between the phase of the field and the phase of those particles which arrive a bit late or early to be responsible for the bunching. Very simply speaking, earlier particles encounter a weaker field whereas later ones are accelerated more than the others so that, on the whole, the beam shrinks into groups of particles travelling together. This is a very rough explanation of phase stability, one of the fundamental concept of circular accelerators. Notice, however, that in the IOTA ring particles are not subjected to overall net acceleration.

The effects of bunching and modulation of a proton beam are observable in Fig. 5 where the results of a simulation are displayed in the phase space. Tab. 2 features the key parameters of the two species of particles circulating along the IOTA ring.

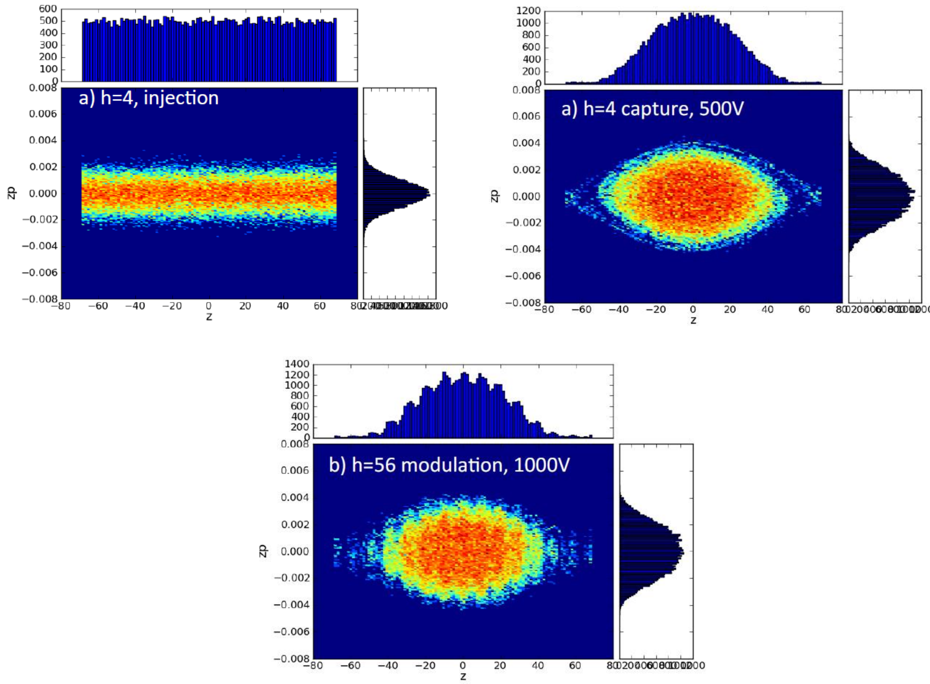

Fig 5. Simulation of the proton beam bunching and modulation. The plots represent the phase space: momentum spread vs. longitudinal position

MAIN PARAMETERS	Electrons	Protons
Kinetic energy [MeV]	150	2.5
pc [MeV]	150.5	68.5
Beta	≈ 1	≈ 0.073
Revolution time	133 ns	1.9 µs
Ring circumference [m]	40	40
Harmonic number h	4	4
Bunching frequency [MHz]	30.62	2.19
Modulation frequency [MHz]	-	30.62
Required gap voltage [V]	1000	500

Tab. 2 Main parameters about the IOTA ring

3. The structure of the cavity

As only one RF cavity is used, the one I have been working on is indeed a joint cavity made of two portions: a disk separator with good contacts with internal and external conductors provides the necessary separation by confining the electric and magnetic fields only in the part where the voltage and the current are provided (Fig. 6). Given these two parts, the cavity is in fact an aluminum pillbox-type cylinder hosting the beam pipe, with one ceramic gap for each side causing the bunching. Cooling plates are set in between the ferrite disks to guarantee thermal stability and prevent the cavity from heating.
In order to decrease the frequency of operation ferrite disks were inserted, 3 on the electron side and 8 on the proton side. This is because when the ferrite surrounds a conductor, the latter will see its self-inductance "magnified" by the high relative permeability of the former which is tantamount to saying that the inductance is increased and the resonance frequency is lowered.
The ferrite material dominates the Q factor as well. It is a measure of the stored energy inside the cavity as compared to the energy loss in one cycle, hence it is a quality parameter. In addition it provides indications about the ratio of the resonance frequency to the bandwidth, which means it specifies how wide the interval of frequencies is at which the response of the cavity is stronger.

$$Q = \frac{E_{stored}}{P_{lost}} = \frac{f}{\Delta f}$$

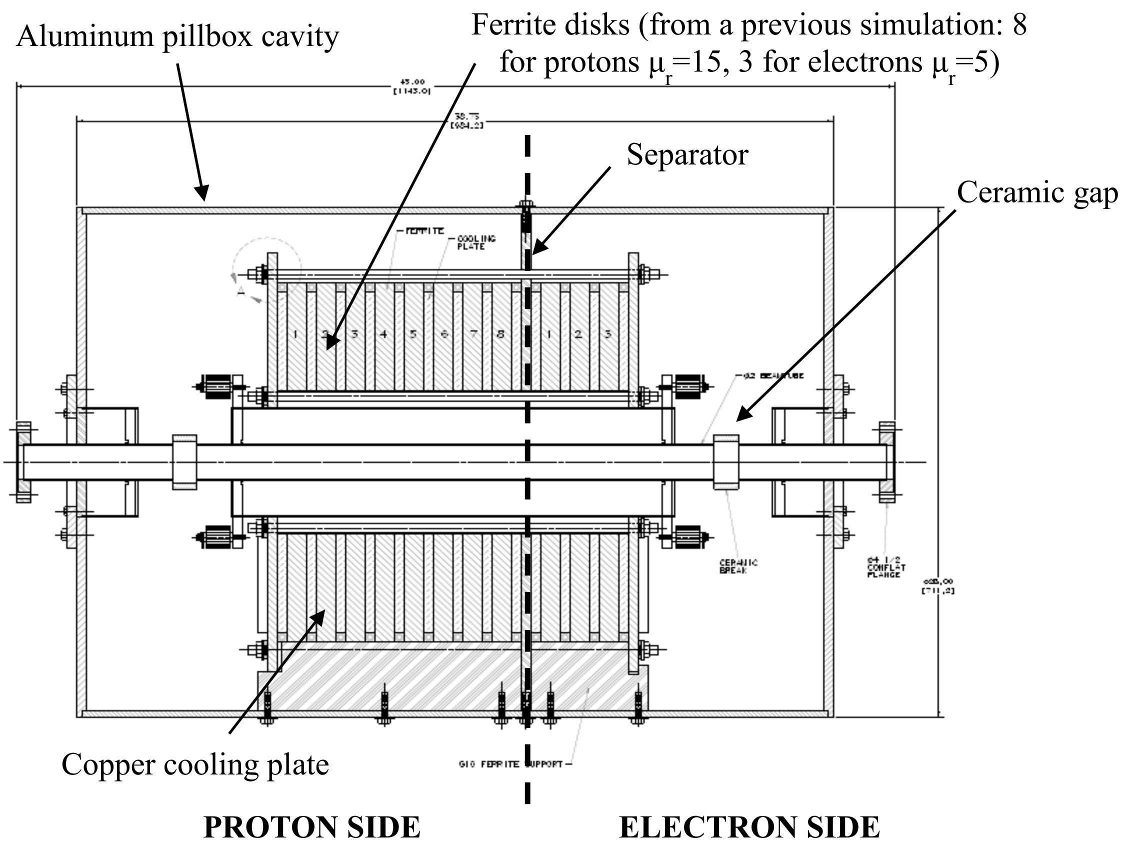

Fig. 6 Lateral view of the cavity: notice the separator in the middle, the gaps on the sides and the ferrite rings

One side of the gap is kept at ground potential, the other at the required RF potential. The current flows on the outer surface of the tube hosting the beam pipe, then through the ferrite and finally on the inner surface of the aluminum cavity; it is confined on the surface because of the skin effect which is particularly effective at RF, that is the skin depth is rather short at these frequencies (the skin depth is indicative of the thickness of the outer portion of the conductor which is traversed by the current).

4. Our main goals: impedance matching and resonance

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, one of the fundamental results of transmission line theory is that the transfer of energy from the source to a load via a transmission line depends on both the line's impedance Z_0 and the load's impedance Z. If the two of them are not equal there will be partial reflection of energy ($\Gamma \neq 0$) back to the source in the form of waves otherwise all the energy will be absorbed by the load ($\Gamma = 0$).

$$\Gamma = \frac{Z_0 - Z}{Z_0 + Z}$$

Also the measurements of the quality factor Q would be useless as we would not be really probing the properties of the cavity but rather those of the loaded cavity. We used a parameter measured by the wattmeter to understand whether the matching had been achieved or not: the standing wave ratio (SWR). It is defined as the ratio of the maximum peak voltage to the minimum value of the standing wave caused in the line by the superposition of the forward and reflected waves. It can be directly formulated in terms of the reflection parameter Γ as well:

$$SWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

If the SWR is 1:1 the line is perfectly matched. The 1:1 ratio is an ideal value, in fact common, reasonable values are for instance 1.2:1.

On the other hand, the voltage and current feeding the cavity and provided by the RF voltage supply should be in phase. The importance of the issue lies in that if there is resonance the current is maximized and, for a given applied voltage, the absorbed power is maximized as well. Notice that resonance implies that their relative phase should be close to zero. As a matter of fact, the problem of ensuring resonance is not trivial at all. One must guarantee the phase is always close to the desired set point within a tolerable range and that whenever a disturbance occurs the system is able to come back to the reference point. During the real operation of the cavity disturbances will occur in the form of loading due to the passing of the charged beam.

It was proposed to fulfill the requirements mentioned above by means of a control system based on a feedback loop (see below). The idea is the following. The resonance frequency of a RLC circuit depends on both L and C, precisely it is inversely proportional to the square root of both L and C. Therefore, by properly changing the capacitance it is possible to reach the resonance condition at the desired frequency, which is fixed once and for all: about 2 MHz for protons and 30 MHz for electrons. At resonance the load becomes purely resistive as the inductive reactance and capacitive reactance cancel out and the current is maximized.

Both conditions, impedance matching and resonance, are mandatory for the optimum transfer of energy to the cavity, which is indeed the ultimate objective. Here are our goals: verify that it is possible to achieve a steady state accuracy of the phase no greater than ±0.5° by employing the resonance control system; verify that the same system is able to recover the set point after a perturbation at most as large as 40°; ensure a SWR smaller than 1.2:1 (or equivalently power loss less than 0.8%). Regarding this last issue, we mention 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 we were indeed testing the cavity and improving the SWR.
For clarity, I point out here that both tasks had partially been completed for the electron side of the cavity at ≈ 30.62 MHz when my internship started and indeed that I took part in the final phase of testing for that portion. My duty has been to perform similar operations for the proton side at a different frequency (≈ 2.2 MHz).

5. The electrical model of the cavity

For a better understanding of the electrical properties of the cavity and of the strategy adopted to deal with our purposes refer to Fig. 7 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 (calculations show the gap capacitance should be approximately 30 pF). The resistor is associated to the resistivity of the path travelled by the current. During one measurement we found out that it is about 115 Ω by simply using Ohm laws and measuring the gap voltage and the lost power; the result is in agreement with the expected value.
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

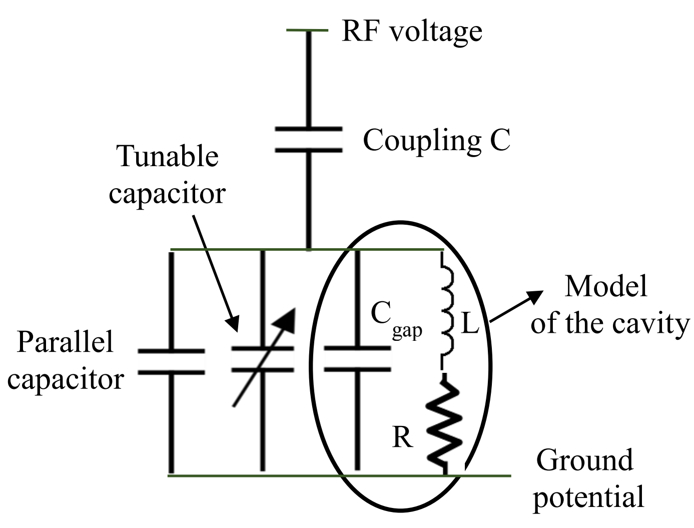

Fig. 7 The electrical model

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.
By referring to the scheme it is possible to calculate the expressions for the quality factor Q and the resonance frequency ω; here are the results of simple but tedious computations (C_{tot} is the sum of the three capacitors):

$$Q = \frac{1}{R}\sqrt{\frac{L}{C_{tot}}}$$

$$\omega = \sqrt{\frac{1}{LC_{tot}}}$$

6. The PID feedback loop

My work continued what had already been initiated by a former intern, Gerrit Bruhaug. He wrote a program for the control of the cavity's driving system by means of a PLC, a digital computer commonly encountered in automation of electromechanical processes. The PLC reads a number of parameters (power delivered to the cavity, phase, impedance, SWR…) from a wattmeter, communicates with a computer, with a potentiometer and a stepper motor via the motor driver. The latter, in turn, controls the variable capacitor.
Therefore the heart of the controlling system is the ladder logic based program. Ladder logic is a programming language based on a graphical representation of the relationships between inputs, outputs, switches, logical checkers and actuators which strongly resembles a ladder with two vertical rails and a series of horizontal rungs. Somehow, ladder logic is a rule based language with rules being represented by the rungs: the output on the right of the rung is activated only if a path can be traced from the left to the right, which means only if all the previous elements are energized as well.
Essentially the program consists in a feedback loop and in a PID control. Assigned the desired set point for the phase, the PLC computes an output on the basis of the error, that is the distance of the actual phase from that point; there are three contributions to the calculation stemming from the error e(t): proportional (P), integral (I), derivative (D).

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

The three parameters K can be adjusted by the user if they have some knowledge of the optimum values or can be figured out by the PLC itself before starting the tuning. Then, on the basis of the computation, at the end of each scan of the ladder program, one each 500 ms, the PLC updates its output which is the number of steps the stepper motor needs to move to modify the capacitance. In the long run, the feedback loop should ensure that the control system catches the set point. The scheme in Fig. 8 shows the network of devices needed to control the cavity, from the power supply and RF amplifier to the stepper motor. Notice that the control action is required for both the electron side and the proton side, hence there are indeed two such similar networks.

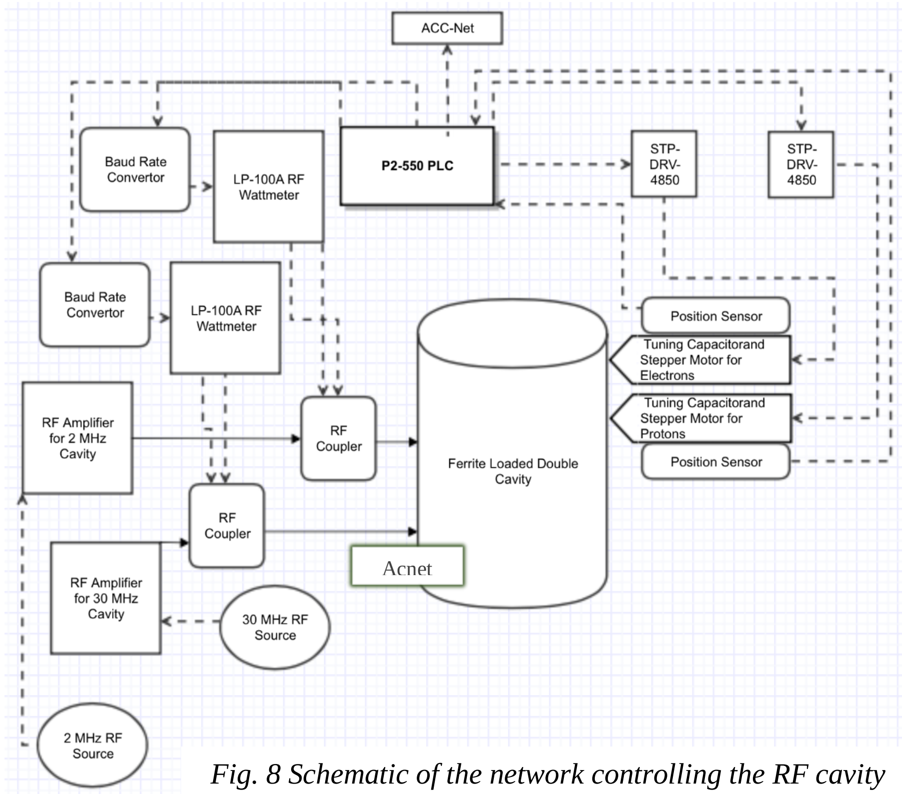

Fig. 8 Schematic of the network controlling the RF cavity

7. The test at 30 MHz

After the necessary training and study required to catch up with the project, I began to contribute to the assembling of the cavity and to the final phase of development of the program and testing. In fact, before actively participating in the project, I spent many days to become familiar with the physics of accelerators and, above all, with the ladder logic program which plays so an important role in the control of the cavity.
Gerrit and I checked the ladder-logic program on the electron side of cavity first at ≈ 30 MHz: as required that consisted in ensuring the control system was able to force the phase to the set point and recover it after a perturbation. Impedance matching had already been ensured for the electron side.
Notice that the cavity was still uncompleted. Moreover, the first measurements and testing were performed by using substitute parts as not to damage the original pieces in case something could go wrong. For instance, the actual variable capacitor was replaced by an auxiliary one because if by accident the number of steps sent to the driver by the PLC had been too large the capacitor could have been broken down. Another example is the ceramic gap: the ultimate gap is very delicate and very expensive, thus it could not be used right from the start.
The test was successful for the program managed to reach and maintain the desired phase, even in presence of disturbances. By observing two examples of plots recorded during one such test (Fig. 9), one can have a proof of the reliability of the system: in response to a large perturbation ($\approx 5^\circ$), the system is able to recover the nominal phase after a few oscillations. Notice that during real

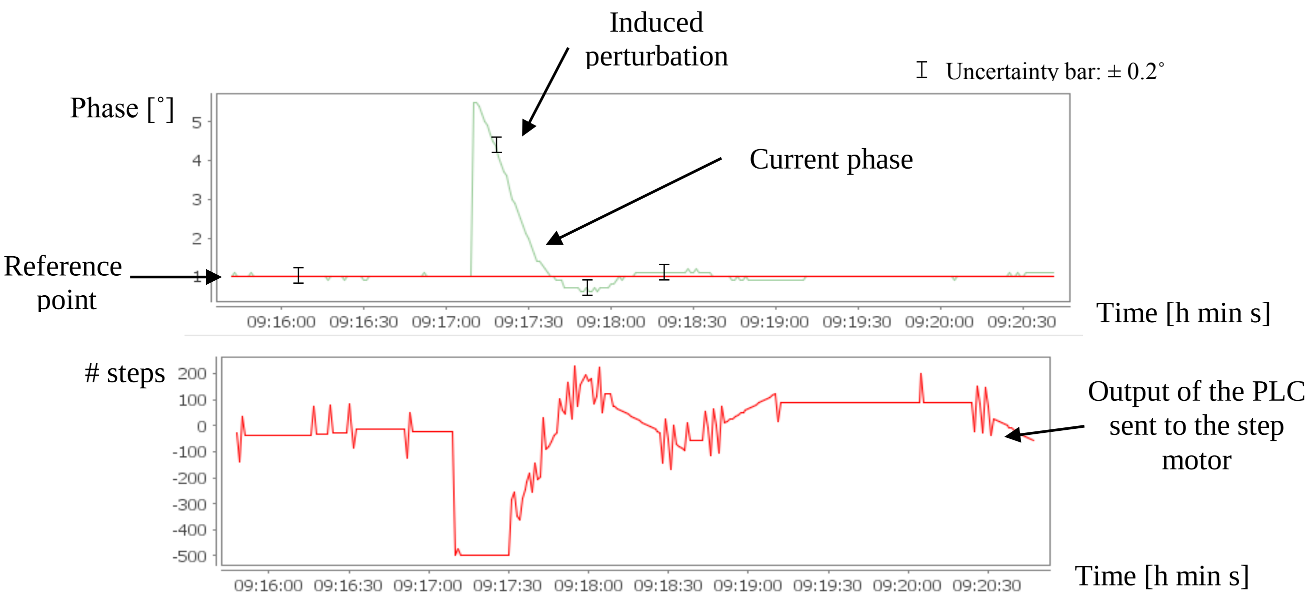

Fig. 9 Exemplary plots of phase and output of the PLC in response to a perturbation; above current phase in degrees vs. time, below number of steps vs. time

operations much smaller perturbations are expected (a few tenths of degree) due to the beam passing through the cavity, thus the settling time will be much shorter as well.

8. Next steps: moving the cavity and preparing the experimental setup

Actually the IOTA ring is currently under construction and several people are participating to the operation. As the cavity had initially been set up in a different building, before continuing the test on the proton side and starting any measurement, the cavity, the parts required for its completion and the whole instrumentation had to be physically translated into the final position (Fig. 10). Needless to say, that took several days to be completed and particular care to avoid any damages. Once everything had been moved, I prepared the experimental setup, that is to say all the electrical devices and connections forming the network and the feedback loop required to feed and tune the cavity. A very useful reference scheme which helped me a lot in establishing all the connections is that represented in Fig. 8.

The feeding of the cavity by the RF voltage supply and the RF amplifier was 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. Thus, during this phase it has been a matter of finding by trial and errors the values of capacitance suitable to satisfy our requirements.

The feasibility of the tuning of the cavity at 2.19 MHz has been accomplished with the reference point kept at 1° instead of using 0° for two reasons: undershoots and oscillations are visible (they

Fig. 10 Hard work!

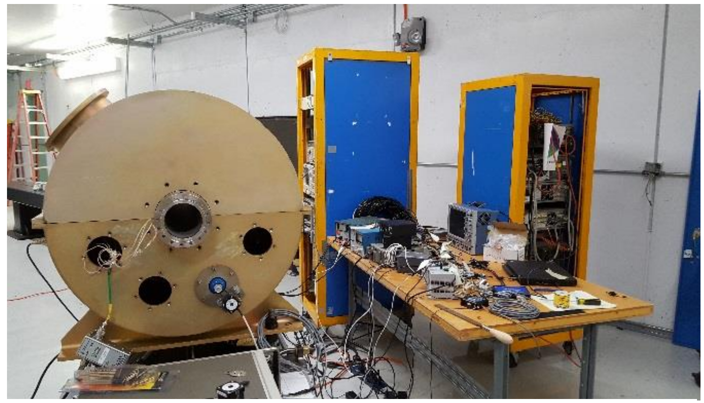

Fig. 11The cavity and the experimental setup

could not be with 0˚ as nominal value because of the incapacity of the RF vector 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 separator was placed in position and the pillbox cavity completed by accommodating the top part as well (Fig. 11). The final beam pipe has not been added yet because of its extreme delicacy. I placed the tunable capacitor in parallel to the gap and mechanically linked it 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. The motor provides the torque while the potentiometer is required to feedback the information about the current position of the motor itself (it is not possible to receive data about the position directly from the motor and hence a potentiometer is needed).

9. A mechanical problem

A 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

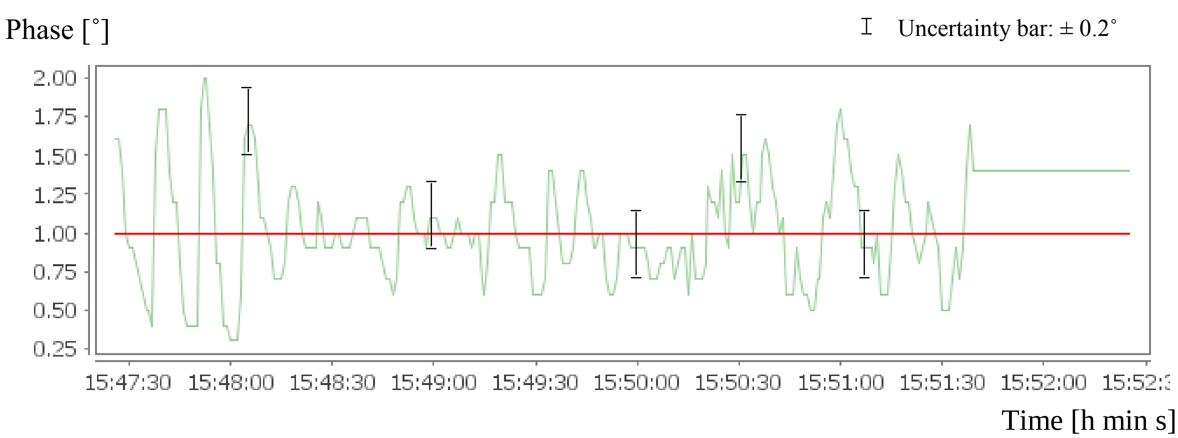

Fig. 12: The uncontrolled motion of the shaft produces undesired oscillations about the reference

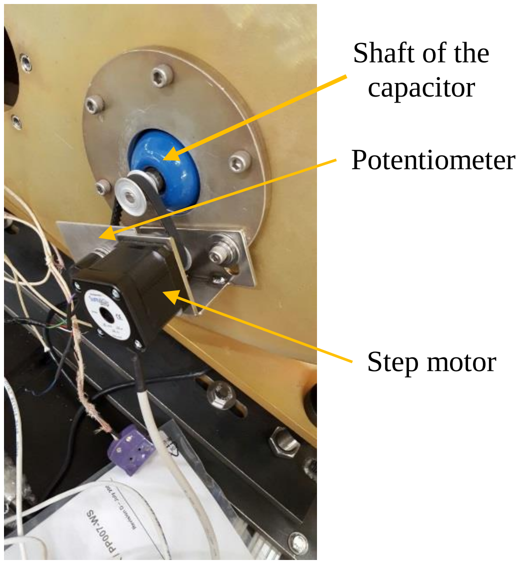

Fig. 13 The original arrangement

Fig. 14 The temporary arrangement

graph of Fig. 12 (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 up and down of the shaft (Fig. 13). Obviously these slight deflections 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; at the moment the idea is to purchase and use a metallic bearing to support and keep the capacitor's shaft stable.

Nevertheless it was managed to continue the test by removing the potentiometer from the pulley system (Fig. 14). Having a two-wheel pulley system instead of three proved to be quite satisfactory: deflections were now unperceivable. Of course that did not allow us to receive any feedback on the position of the step motor, yet it was not a problem because we were still able to perform the tuning: the feedback loop was not broken. The only thing we needed to take care of was 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 we had got close to resonance the PID loop would produce only a tiny rotation of the step motor because the required adjustment was rather small (in other words the error was pretty small). Notice that the information about the phase is measured via the wattmeter and not through the potentiometer, hence the PID feedback loop was not broken.

Thus, in these conditions we tried to tune the capacity to reach the resonance condition also on the proton side. Before starting the PID tuning we let the program run the auto-tuning. As already mentioned, 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 we updated the new values into the program datasheet. As a matter of fact during the test we found by trial that slightly different values were able to provide a better response to perturbations: reduced overshooting and smaller oscillations about the set point (see below).

10. Some noise

Another minor problem was observed during the test due to heating. Observe, for example, the last graph. Though the phase is always quite close to the reference value, oscillations occur. We believe that these fluctuations are the response to some kind of noise, in particular the heating of the cavity. In fact, as the pattern seems to be stationary we think 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 likely to be produced by heating due to ohmic losses and, indeed, that is the reason why cooling plates were inserted. The explanation is supported by two observations: we observed a slight increase in the cavity's impedance, as shown by the wattmeter; the step 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, we found that 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 base of the error is smaller.

11.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 only on the capacitors may not be sufficient for an approximate tuning. There is another reason for being suspicious about a large 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, we planned to verify the efficacy of the resonance control system in catching the reference phase point. In fact, the tuning has to be 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.

Fig. 15: 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 bar corresponds to ± 0.2°in all cases. 2 shows the output of the loop computation (number of steps vs. time).

In Fig. 15 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 (referred 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.
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 measurements produced similar results which were 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.

12. 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 created 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.

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Link

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