Repurposing the 2.5 MHz bunch rotation cavity design for continuous wave operation in the Recycler Ring

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The 2.5 Mega-Hertz (MHz) radio frequency (RF) cavity design, which was previously being used for bunch rotation in the Main Injector prior to the Tevatron shutdown, is being repurposed for use in the Recycler Ring. New experiments, g-2 and Mu2e, require bunch rotation prior to beam injection. The cavities will essentially remain unchanged, except that they will need active cooling due to new load requirements. While operating as the Main Injector's bunch rotation units, the 2.5 MHz cavities were operated in 80 millisecond (ms) pulses on approximately 15 second intervals. The new experiments require the cavities to have the capability to operate continuously. This increased load will result in intolerable heat buildup, which will detune the cavity; therefore, a new 2.5 MHz cavity with a water cooling system is currently being developed through the RF department. The following is a brief study of RF cavity design, the methodology used in measuring the ferrite, an overview of the bunch rotation process, and the necessary improvements to the current 2.5 MHz systems.

INTRODUCTION

Prior to the shutdown of the Tevatron at Fermilab, five 2.5 MHz RF cavities, currently attached to the Main Injector, were used for bunch rotation. New experiments, such as g-2 and Mu2e, require a similar process to take place in the Recycler. A modified version of the current 2.5 MHz cavities is under development; the Recycler will need a total of seven new ferrite loaded 2.5 MHz cavities. After reclaiming the ferrite cores from the Main Injector models, an additional 72 new ferrite cores will need to be ordered and individually tested to ensure a correct match with the system. To accomplish this, a small test fixture was designed and manufactured at Fermilab, which will allow the ferrite cores to be tested prior to installation. Once in the Recycler, the 2.5 MHz cavities will be used for bunch rotation, which will take twenty-one 53 MHz bunches and capture them with a single 2.5 MHz bucket. The 2.5 MHz cavity will then rotate the entire group through phase space so that the difference in time/space between the particles near the front and rear are minimal. Though the role of the 2.5 MHz cavity will essentially be the same between the Main Injector models and the Recycler models, the requirements of the experiments necessitate that the 2.5 MHz cavities have the capability of continuous wave. Unlike the pulsed operation which took place in the Main Injector, continuous wave means that the cavities will continuously produce a 2.5 MHz signal. The new cavities will therefore need to be redesigned and fabricated in a way which will transfer energy out of the ferrite; otherwise, the cavity will fail to resonate at the desired frequencies.

RF CAVITIES

RF cavities are used to transfer energy to charged-particle beams as efficiently, and quickly, as possible. This is done by creating an electric field parallel to the axis of the beam. A direct current (DC) voltage could be used, and is used in lower energy experiments, but at high energies this is not feasible. DC accelerators, also known as electrostatic accelerators, need a potential difference equal to the desired energy. At the current level of electrostatic technology, this is not feasible. In a circular path, such as a synchrotron's ring, this constant potential would also mean that the particles would experience a net zero electric field as it moved around the circumference of the ring.

The electric field inside an accelerating cavity is created by capacitive gaps in the beam pipe. The surfaces of the gaps vary in potential, which results in an electric field between the two surfaces. By using a time varying signal, the potential of the surfaces can alternate between set values. This solves the issue of zero net work on the object by reversing the direction of the electric field as the particle moves down the beam pipe. As a result, the particle experiences a cumulative effect due to the electric fields and can experience a non-zero net work.

Acceleration is one of the main purposes of RF cavities, but it is not the only purpose. As is described in more detail later, the 2.5 MHz RF cavities are instead used to manipulate the shape of the beam, and not necessarily to change the energy of the beam itself. This process will alter the intensity of a portion of beam by putting more material in a smaller space, without changing the net energy of the system.

An issue which arises, when using low frequency cavities, is the physical space needed to resonate a large wave length. This is partly resolved by using quarter-wave or half-wave resonance. The 2.5 MHz cavity design uses two quarter-wave resonators, set end to end. This type of design requires approximately the same amount of space as a half-wave resonator. For reference, half the wave length of a 2.5 MHz signal in free space is sixty meters.

Ferrite cores provide a solution to this problem by slowing down the phase velocity inside the cavity. Doing this reduces the required length from 60 meters, down to 1.7 meters. Also, without ferrite, the phase velocity propagates faster than the speed of light. As matter is unable to move this fast, the phase velocity must be slowed so that the signal and the beam can be synchronous (Gerigk, 2011).

Ferrite is a magnetic material which is used for its high relative permeability and low electrical conductivity. These values change as frequency changes, and ferrite from different manufacturers has been observed to have greatly varying attributes (Dey, 1996). As such, the ferrite used in the new 2.5 MHz cavities will need to be tested to ensure that they will properly match the system.

FERRITE

A. Testing Permittivity

To test the permittivity of a ferrite sample, a simple capacitor was created using two disks of aluminum. This was done by using one of the disks as the base, then centering the ferrite core on that disk, and finally placing the other aluminum disk on top. A vector impedance meter (HP 4193A), with an attached probe, was connected to the two plates and driven at 2.5 MHz. This frequency was chosen to match the frequency of the cavities in which the ferrite will be used, as the properties of ferrite change as a function of frequency. The equation for a parallel plate capacitor is:

Where C is the capacitance, A is the area of the conducting plates, and d is the distance between the plates. Because this capacitor can be thought of as three capacitors in parallel, two filled with air, and one filled with ferrite, the equations for total capacitance becomes:

In this case, A_2 is the surface area of the ferrite, while A and A_2 correspond to the areas either radially outside, or radially inside the ferrite core. The capacitor will then resonate at some frequency, and assuming negligible skin affects at this time, the system is modeled as purely reactive. Combining the capacitance and inductance relationship at resonance, with the function for impedance, will return inductance as a function of impedance, the drive frequency and the resonant frequency.

Using the measured results of the vector impedance meter, total inductance can then be found. Taking the total inductance and entering it into the resonance equation will return total capacitance. Then, by subtracting out the two air capacitors, it is now possible to solve for relative permittivity.

B. Testing Permeability

Testing for permeability was done in a test fixture which resembles two extremely short coaxial cables in series. The cavity was driven by a loosely coupled port on the side of the cavity and was measured using a network analyzer (Agilent Technologies E5071C) with an attached high impedance probe. To find the wave velocity, an approximate relative permeability was taken from the manufacturer data sheet. This results in a lambda over four of .75 meters, which is much longer than the length of the test fixture. Because of this, we can assume that the phase will not have passed through ninety degrees, and as such is inductive. To find inductance, the standard coaxial inductance per unit length formula was used.

Below is a top view of the cavity. Note that the cavity's outer radius was not constant; instead it changed discretely, one inch above its base.

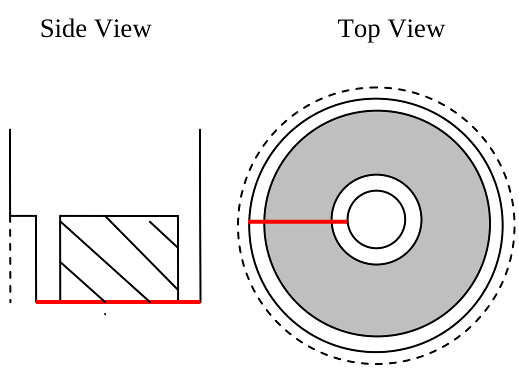

Figure 1: *Diagram of the test cavity*

The radii were measured with the innermost radius being r_1 and the outermost radius being r_5. In the radial direction, the different materials will look like three inductors in series, and in the Z axis—the axis coming out of the page in the "Top View" of Figure 1—the two different inductances per unit length are also in series. This, then, solves for the total inductance as a function of the relative permeability, length, and radii. Because this results in two unknowns, the total inductance is solved for first by using the known capacitance and resonant frequency, and entering it into the resonance equation. Using that value of total inductance (L_t) allows us to solve for μ_r.

Now, with a means to measure the inductive and capacitive properties, ferrite samples, from various manufacturers, can be obtained and tested. This will maintain consistency in the ferrite loaded 2.5 MHz cavities.

BUNCH ROTATION

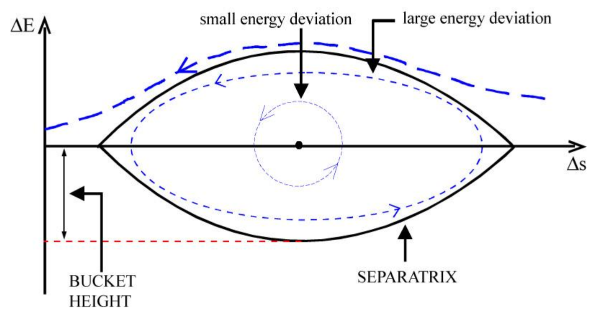

Figure 2: *Depiction of a single bunch rotating through phase space. The frequency of this bunch is not declared, but single bucket rotation is independent of frequency (Simon, 2003)*

Bunch rotation is a term used to describe the natural oscillations of particles between deviations in energy and deviations in time/space. This process takes place continually inside the beam and is a result of the particles within a particular bunch arriving at the gap inside an RF cavity at slightly different times. An ideal particle will always receive the right amount of force, and arrive at the correct time, but the particles in front of, or behind, the ideal particle will experience forces slightly too great, or too small. Because of this, the particles near the front will slow down, with respect to the center particle; while the particles near the rear will speed up, again with respect to the center particle. This is what causes the deviations in energy, as some particles begin going faster, or slower, than others. Eventually, the particles in the front and rear of the bunch get as close to the ideal particle as they will ever be, this is the point where the deviations in time/space are a minimum. The oscillatory motion doesn't stop there; the particles which were in front, but moving slower than the ideal particle, eventually find their way in the back of the bunch, and the particles which were in the rear, but moving faster than the ideal particle, move to the front. Once the front and rear particles have switched places, the energy differences minimize, and the time/space spread is at its maximum. This rotation through phase space will continue, and be contained, so long as the particles stay inside the bucket area, which is defined by the separatrix—see figure 2.

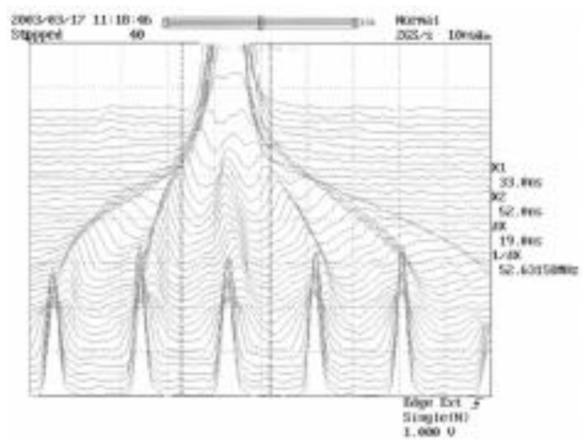

Figure 3: *This image shows six 53 MHz bunches being rotated together through phase space. From bottom to top, notice that the peaks merge (Dey, 2003)*

Another form of bunch rotation, which is used to increase the particle density, will be the purpose of the new 2.5 MHz cavities scheduled for installation in the Recycler. Because the wavelength of 53 MHz is much smaller than the wavelength of 2.5 MHz, twenty-one 53 MHz bunches can fit inside a single 2.5 MHz bucket. This causes all of the bunches, in the new 2.5 MHz bucket, to draw towards the center in the same manner, and for the same reasons, as the single bunch rotation case. This process increases the energy spread within the new bunch, but significantly reduces the time spread. For reference, when the new 2.5 MHz cavities are installed in the Recycler, they will be able to rotate 90% of the material held within twenty-one 53 MHz bunches—which is approximately 400 nanoseconds long—into a 120 nanosecond time window, with a rotation time of 133 milliseconds (Dey, 2013).

CAVITY UPGRADE

In the past, the rotation process happened in pulses and the heat buildup generated by this was well below critical thresholds. The new experiments necessitate the cavities to be able to operate continuously in the future; this is why water cooling elements will be needed in the new 2.5 MHz cavities. Determining the water flow needed was not an overly complicated process, the main difficulties are drafting a system to deliver the water, and understanding the impact this new system will have on the cavity itself. Placing aluminum plates in between each ferrite core will change the characteristics of the cavities. As such, the RF department is currently modeling and drafting the new cavities so that they will operate properly under the new requirements.

CONCLUSION

The transition plan for the 2.5 MHz cavities is covered under the Muon Campus Internal Project Assessment, “Recycler RF API.” This project is still in its initial stages and has a projected completion year of 2017.

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