Resonant Cavity Field Profiler

ECE 445 Design Document

Team 31

Salaj Ganesh, Max Goin, Furkan Yazici

TA: Stasiu Chyczewski

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1. Introduction

1.1 Background

Radio frequency quadrupole (RFQ) linear accelerators offer a compact solution for obtaining low velocity, 0.01-0.06c, particle beams. RFQs have a distinct advantage as they offer very good transverse beam focusing, can accept a DC particle beam, and produce fine bunches. Good bunching and focusing is a requirement for input into many higher energy linear accelerators so RFQs are often used as a first stage in a series of accelerators. These properties also make them well suited for accelerating heavy ions. RFQs have 4 veins whose tips are machined such that the tip varies sinusoidally along the central axes of the accelerator with an increasing wavelength. This modulation of the tip geometry is the principal component that allows for a longitudinal electric-field component to accelerate ions. The veins are driven by a magnetic field coupled with RF excitation with altering phasing for each vein [3].

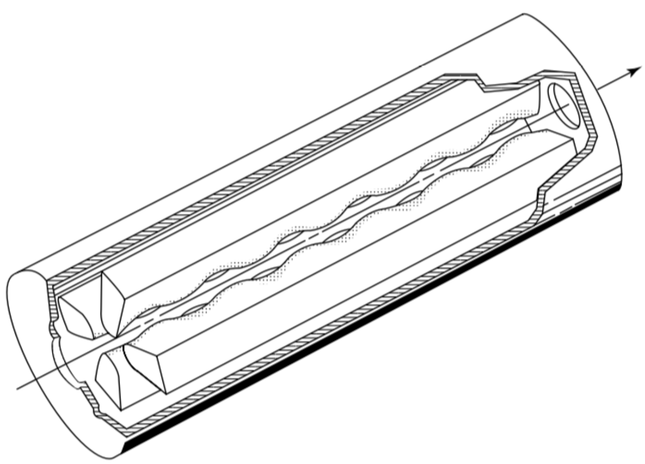

Figure 1: Cross-section of an RFQ accelerator. The modulation of the 4 veins tips can be seen clearly but the increasing wavelength along the particle path (arrow direction) is not represented.

1.2 Problem

This project proposal was submitted by Starfire for designing a device to tune Resonant Cavity Particle Accelerators.

The design process of Resonant Cavity Particle Accelerators requires fine characterization of their electric field for design verification. This is typically accomplished by pushing a metal bead through the cavity where the magnetic field is the strongest. This results in a small, but measurable change in the resonant frequency of the internal cavity. This frequency offset gives the operator an indication of the strength of the magnetic field displaced by the bead. This is then used to estimate the electric field strength and uniformity. This is typically done manually, with a user making small changes to the position of the bead and measuring the resulting frequency shift. This process can be very time-consuming and take a single user up to two days to accomplish.

1.3 Solution

A stepper motor will move the bead through the cavity while a microcontroller will measure any resonant frequency offset and log the current position. This device will move the bead through all 4 cavities of the accelerator while simultaneously making measurements to estimate the current field conditions in response to the bead. The frequency offset will be controlled by the MCU and the setting time of the control loop will be the limiting factor in the time it takes to perform a complete characterization. This will help technicians properly tune and characterize cavities to obtain optimum performance.

We will work with Tom Houlahan, the engineer responsible for the project, and will meet with him regularly to discuss the project. Starfire will be providing a test cavity for the purposes of design verification and testing. Tom would like the characterization to take roughly the amount of time to get a cup of coffee or roughly 5 minutes at minimum.

1.4 Visual Aid

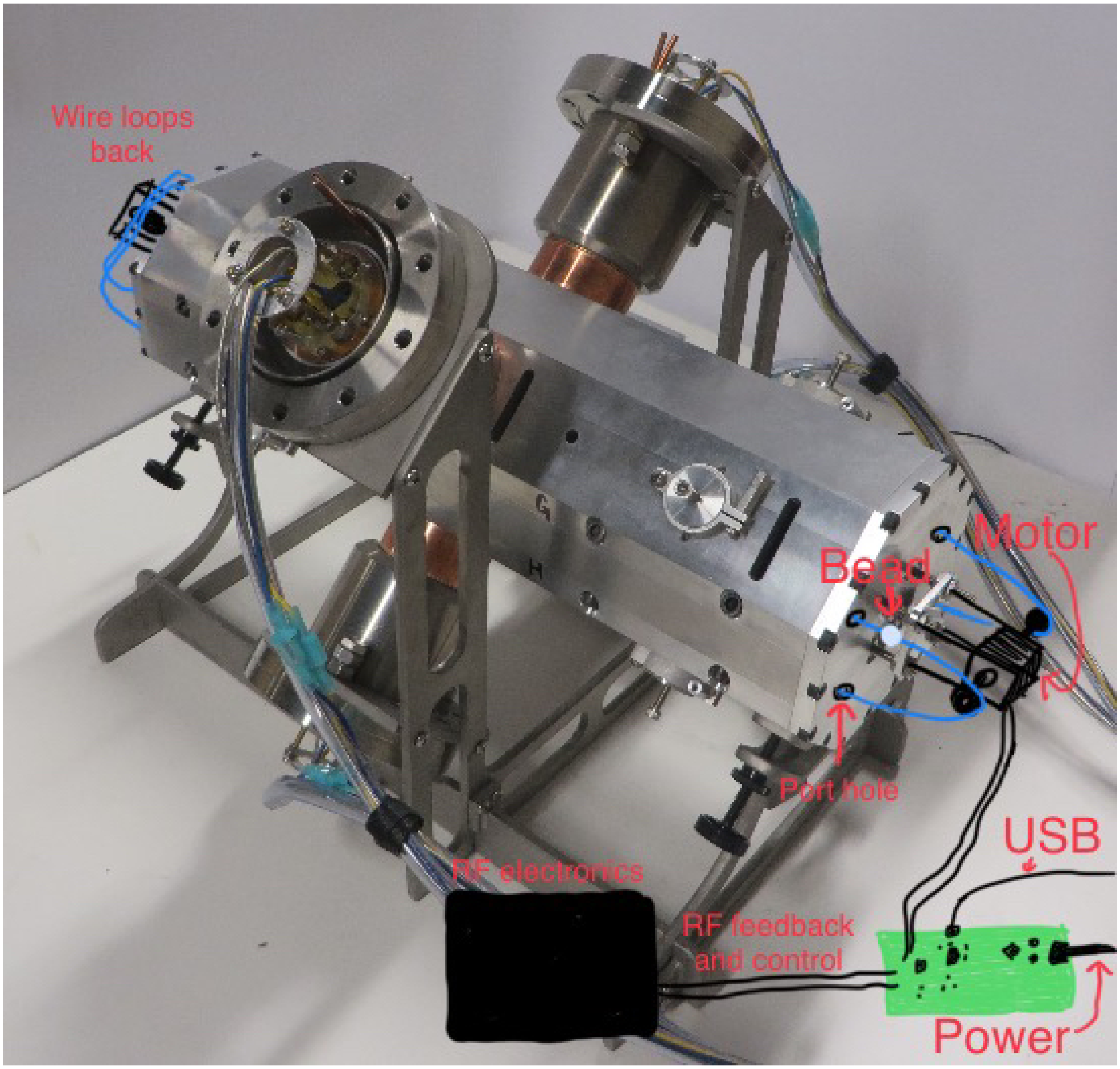

Figure 2: Basic setup with the test cavity. Our board is shown in green while all other materials are to be provided by Starfire

1.5 High-level requirements list

1. Pull a bead through the cavity and record the responding resonating frequency. It will continue and calculate the bead position for an optimal resonating frequency. These measurements should occur at every 1mm interval of bead movement.

2. Characterization will complete in a matter of minutes (five minutes was requested). The entire characterization process will not require any input from a user. Once complete, it would then notify the user of its completion using notification LEDs.

3. Data will be logged on a PC for later use so users can refer to it later. The data should include the position of the bead and its corresponding field characterization.

2. Design

2.1 Block Diagram

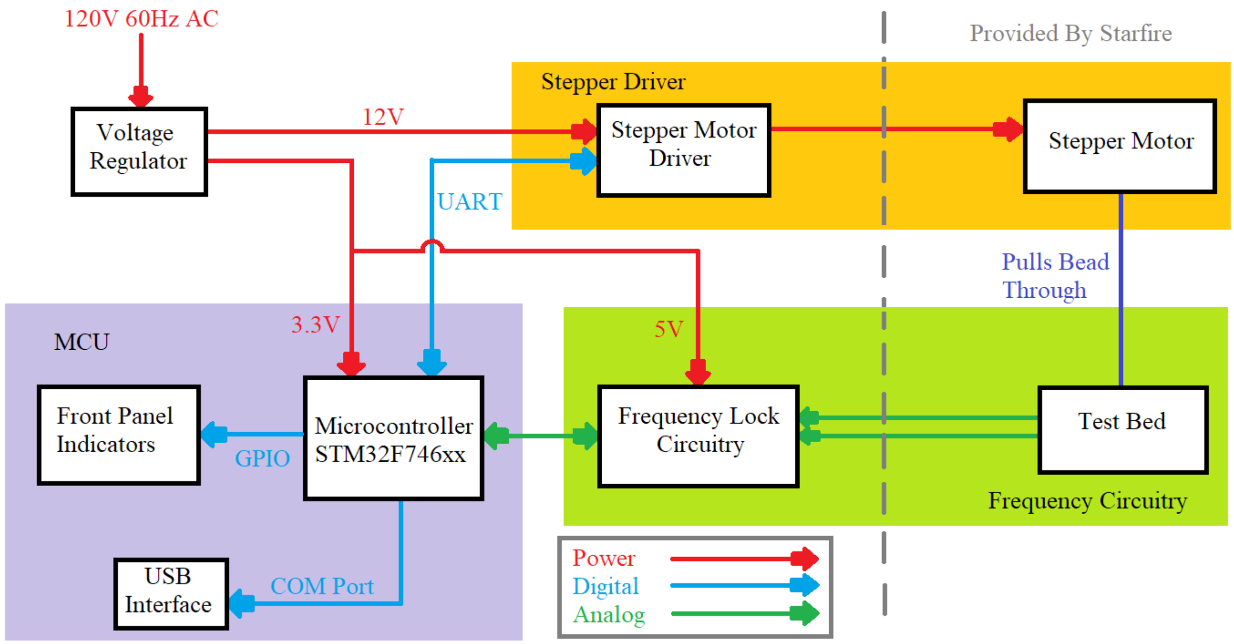

Figure 3: Block Diagram

2.2 Subsystem Overview

2.2.1 MCU

Supplies drive signals to a stepper motor to move the metal bead through the 4 quadrants of the RF cavity. Controls a front panel to indicate the current state of the system. Communicates to an external computer to allow the user to set operating conditions and to log position and frequency correction data for further analysis. Samples feedback signals from RF front end and issues corrections to the PLL circuitry through the DACs. We chose the STM32F746 due to availability. This microcontroller is highly capable and notably has 2 12bit DACs, 3 12bit ADCs, 4 UARTs, 320kb onboard SRAM, and USB 2.0 FS support. These will fully satisfy our requirements for a microcontroller.

2.2.2 Frequency Circuitry

Maintains a drive frequency that is equal to the resonant frequency. A series of op-amps form a control loop from output signals from the RF front end. They will also filter the feedback signals before sampling by the ADCs. The LM324 is a good option for this as it supports up to 32V and is available in a quad package.

2.2.3 Stepper Driver

We will be using a Trinamic TMC2202 stepper motor driver IC. The TMC2202 can supply up to 1.2A RMS and up to 256 micro steps offering high positional performance and smooth operation. This IC can be easily interfaced with a UART port from the MCU. Over UART, you can issue speed and distance commands and read back the current positional data. A small momentary contact switch will be used to “home” the bead to ensure the same starting location before each profiling pass.

2.3 Subsystem Requirements and Verification

2.3.1 MCU

Requirements	Verification
1. Communicate with a PC over USB for data logging	1. Connect MCU to multiple different computers and operating systems and ensure it appears for data interactions.
2. Utilize the ADC on microcontroller to convert analog signals from Frequency-Lock Circuitry to receive data from RF cavity	2. Connect a function generator to the MCU ADC and have it output in the same range as the Frequency-Lock Circuitry

2.3.2 Frequency Circuitry

Requirements	Verification
1. Amplify an analog feedback signal by a multiplier of 1000x 2. Sum the amplified feedback signal with a frequency set signal	1. Connect a function generator and have it output a signal in the mV range and ensure the signal gets amplified by correct multiplier 2. Input two analog signals and ensure the output is as desired

2.3.3 Stepper Driver

Requirements	Verification
1. Precisely control a Stepper motor (provided by Starfire) to move a bead through the RF cavity with 1mm movements. 2. Communicate with MCU on the current position of the bead and reset it to a given position if needed.	1. Connect a test bead to the stepper motor and move it slowly while measuring the displacement of every tick. Each tick should displace the bead around 1±0.2 mm. 2. Write a test program on the MCU to randomly move a test bead to a certain location and reset it multiple times. Should always reset to the same position

2.3.4 Voltage Regulator

Requirements	Verification
1. Output the required 15V, 9V, 5V, and 3.3V (± 5%) needed for subsystem operation 2. Properly filter the analog output to prevent power supply noise interfering with sensitive measurements	1. Supply AC and measure outputted voltages using a voltmeter 2. Ensure the analog power lines remain constant (± 1%) with a large load on other power lines (stepper motor).

2.4 Tolerance Analysis

To meet the requested five-minute acquisition requirements, the bead must be able to traverse the cavity four times (once for each quadrant) in roughly 300 seconds. The cavity is one meter long so this equates to a required traversal speed of 1.33 cm/s. We would like to make a measurement of the beads' field displacement roughly every 1mm which represents an ADC sampling rate of around 14Hz. This is well within the capabilities of our microcontroller's maximum conversion rate of 2.4MSPS.

Phasing of the RF power injected into the cavity is critical for the accelerator to function properly. The phase must be within 1-degree with respect to the particle bunches accelerated through the cavity. This 1-degree accuracy requirement is subjective but will meet the requirements as set forth by the responsible engineer at Starfire. This is because the bunches ride on the peak of the oscillating longitudinal electric field. If the bunches are lagging slightly to this peak they will not be accelerated, and if they are ahead of the field peak they will not be accelerated as much. This results in bunches naturally stabilizing just around the peak as lagging particles fall into the succeeding bunch and particles moving slightly faster than the bunch will experience a slightly smaller force compressing the bunch to the peak of the electric field. If the RF phasing starts to drift the size of the bunch along the longitudinal axis will grow which will result in decreased performance. To control the phasing, the RF board uses 2 180 degree phase shifters in series to obtain a full 360-degree phase shift capability. The part chosen is a JSPHS-661 which offers 0-180 degrees within a 0-9v control voltage range. We are operating within the 600Mhz band so, according to the datasheet, a 9v control voltage results in a total phase shift of 188.21-.02 degrees [4]. This results in 9/(188.21-.02) = .0478V/degree. To maintain an overall accuracy of 1 degree this means our DAC must be capable of just under 24mV/bit. The DAC driving this signal is a 12bit DAC that is level shifted to the 0-9V range and will therefore offer 9/2^12 volts per bit or 2.19 mV per bit. This outperforms the requirement by a factor of 10.

3. Cost and Schedule

3.1 Cost

3.1.1 Labor

The average salary for ECE graduates at the University of Illinois at Urbana Champaign is around $100,000 per year or around $50 an hour. Assuming each member of our team works for 10 hours per week, for the remaining 12 weeks of the semester, we can estimate the total labor cost this project will require.

$$\frac{\$50}{hour} \times \frac{10\ hours}{week} \times 12\ weeks\ \times 3\ people\ = \$18,000$$

3.1.2 Parts

Part Number	**Description**	**Supplier**	**Quantity**	**Net Price**
STM32F722RET6	32-Bit Microcontroller	STM	1	$13.13
MCP47FEB0202	Dual Channel DAC	Microchip	1	$1.34
629105136821	Micro USB 2.0 Receptacle	Wurth	1	$1.27
LMH6642MF/NOPB	Output Amplifiers	TI	5	$16.25
TMC2100-TA	Bipolar Motor Driver	Trinamic	1	$5.98
TL3305AF260QG	Tactile Switch	E-Switch	1	$0.21
MPM-10-15	10W AC Power Supply	Mean Well	1	$13.44
L7809ABD2T-TR	9V 1.5A Voltage Regulator	STM	1	$1.05
LDL1117S33R	3.3V 1.2A Voltage Regulator	STM	1	$0.50
LM2931ADT50R	5V 100mA Voltage Regulator	STM	1	$1.27
TL780-05CKTTR	5V 1.5A Voltage Regulator	TI	1	$1.74
N/A	Miscellaneous Resistors, Capacitors, Inductors	N/A	N/A	$10.00
N/A	4 layer PCB	PCBway	1	$30.00
N/A	Solder Stencil	PCBway	1	$10.00
Total Price				$106.18

3.1.3 Total Cost

In the best-case scenario, the total price of the project comes out to $18,106.18. However, we may need to buy replacement parts in the case of an unexpected tragedy.

3.2 Schedule

Week	Max	Furkan	Salaj
2/21	Finalize Digital Circuit Schematics	Finalize Analog Circuit Schematics	Finalize Power Circuit Schematics
2/28	Finalize Layout	Generate BOM and select final project Box	Prepare parts order and payment processing
3/7	Setup STM32 HAL	Complete STM32 initialization functions	Complete Stepper motor API integration
3/14	Complete PCB Assembly and initial hardware checks	Confirm Virtual Com Port functionality	Complete ADC initialization and SOC handling
3/21	Complete testing of stepper motor driver and bead homing	Finalize PC side data capture	Finalize CubeIDE project
4/4	Test with cavity		
4/11	Plan for demo		

4. Ethics and Safety

We will be working with potentially high-power RF circuits operating at around 600Mhz. Leakage from the cavity could represent a serious source of interference to communications in the UHF band. This is mitigated by the design of the RF cavity and is outside the scope of our work. This still should be taken into account and the test cavity should not be operated without the tuning port holes open. A fully operational particle accelerator of this class is capable of accelerating particles to energies capable of damaging tissues. This will not be an issue as the cavity will not be under vacuum and therefore not capable of accelerating particles.

We will be working with voltages above 100V which have the potential for dangerous discharges. Capacitors can hold dangerous amounts of charge for extended periods of time after being disconnected from a power source. For this reason, caution should be taken around PCB areas that were energized and should not be touched.

The IEEE Code of Ethics [1] states that we must ensure we work “to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, to protect the privacy of others, and to disclose promptly factors that might endanger the public or the environment.” This is especially important during the COVID-19 Pandemic. We must make sure we clean all lab equipment after use to reduce the chances of infection. When meeting in public locations we also need to follow any and all precautions.

5. References

1. IEEE Code of Ethics.” IEEE, https://www.ieee.org/about/corporate/governance/p7-8.html.
2. Powers, Tom. Theory and Practice of Cavity RF Test Systems. United States: N. p., 2006. Web.
3. T. P. Wangler, “1 Introduction,” in *RF linear accelerators*, 2nd ed., Weinheim: Wiley-VCH Verlag, 2017.
4. *Narrow Band Phase Shifter JSPHS-661+ - Mini-Circuits*. https://www.minicircuits.com/pdfs/JSPHS-661+.pdf.