An Amplitude and Frequency Stabilized High Power Oscillator for Mass Filtering and Multipole Ion Guides

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Introduction

In mass spectrometry, quadrupole ion guides are commonly driven by high voltage oscillators. Such "power supplies" usually provide sine waves which can be described by the electric potential Φ:

$$\Phi = U + V\cos\omega t \qquad (1)$$

where V_o is the zero-to-peak amplitude of a radio-frequency (RF) potential oscillating with angular frequency ω, and U is a DC voltage applied [1]. When a DC bias is applied to the sine wave (namely, when U is not zero), a quadrupole system can be operated as a mass filter.

As shown in Figure 1, two pairs of rods are connected with opposite-polarity RF signal applied electrically, and establish a two-dimensional field in the x-y plane. When the ions travel in the z direction, they will oscillate in the x-y plane while traveling along the z direction [1].

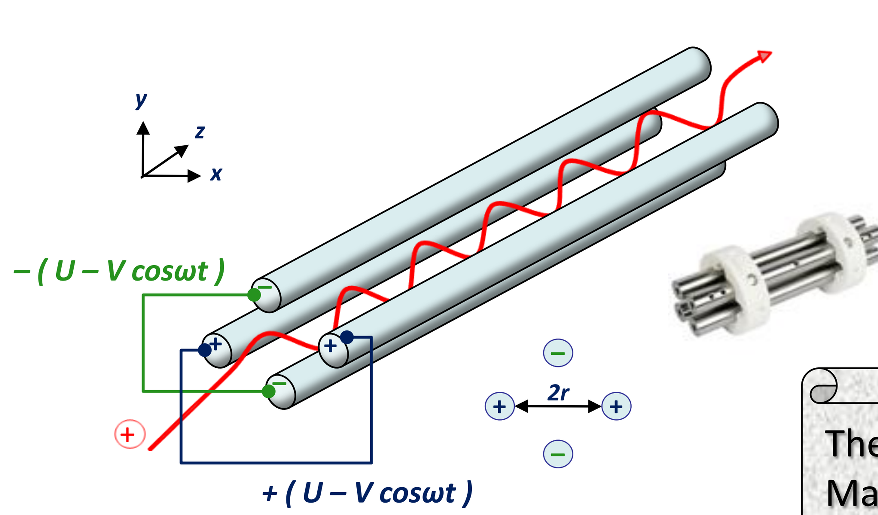

Fig 1. A quadrupole picture, the schematic, and the cross-section view of a quadrupole mass filter

The assumptions for deriving Mathieu Equation:
- Single ion
- Infinite rod length
- Hyperbolic rod surface
- No magnetic field
- No air pressure

The net potential Φ_0 applied to a single ion in the quadrupole can be described as:

$$\Phi_0 = \Phi_{x\text{-}pair} - \Phi_{y\text{-}pair} = 2(U + V\cos\omega t) \qquad (2)$$

The quadrupolar potential at point (x, y) is: $\Phi_{(x,y)} = \Phi_0 (x^2 - y^2)/2r^2$ (3)

Therefore, the x-direction force $\mathbf{F}_x$ acting on this ion at point (x, 0) is:

$$\mathbf{F}_x = ma_x = m\frac{d^2x}{dt^2} = -ze\left(\frac{d\Phi}{dx}\right)_{y=0} = -ze\frac{\Phi_0 x}{r^2} \qquad (4)$$

e = 1.6 x 10^-19 C
z = numbers of e

electric field

By substituting (2) into (4), it will become a Mathieu Equation:

$$\frac{d^2u}{d\xi^2} + (a_u - 2q_u\cos 2\xi)u = 0 \qquad (5)$$

where $a_u = a_x = -a_y = \dfrac{8zeU}{m\omega^2 r^2}$ and $q_u = q_x = -q_y = \dfrac{-4zeV}{m\omega^2 r^2}$ (6)

The solutions to the Mathieu equation can be interpreted in terms of ion trajectory stability in the stability diagrams [1].

Stability Diagram

- There are multiple stability regions (where ion motions are stable in both the x- and y-dimensions). Most quadrupole mass analyzers work in the first stability region

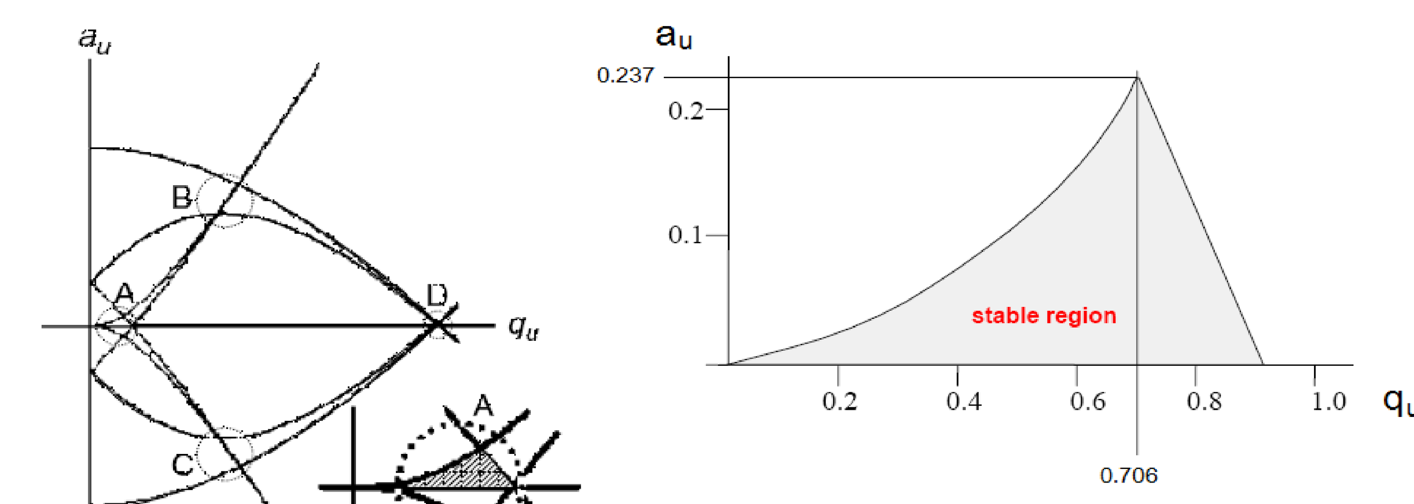

Fig 2. Stability Diagrams [2]

- From equation (6), the stability diagram in a_u/q_u space can be superimposed to U/V space, as shown in Fig. 3.
- By scanning the U and V (while keeping U/V constant) across the tip of the stability regions, a steeper line provides a higher resolution, as long as they still go through the stability areas.

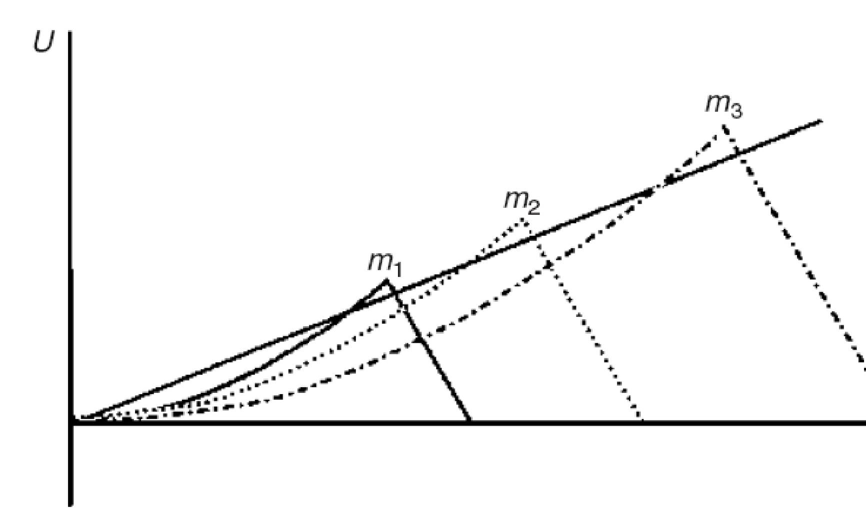

Fig 3. Stability diagram in U/V space, with stability regions for different mass/charge ratios m_1, m_2, m_3, where $m_1 < m_2 < m_3$ [2]

- Mass filtering can be done by adjusting the U/V ratio closer to the "top."
- A power supply with parameters stabilized to 1/10000 is necessary to be able to produce > 1000 resolving power.

Previous Design

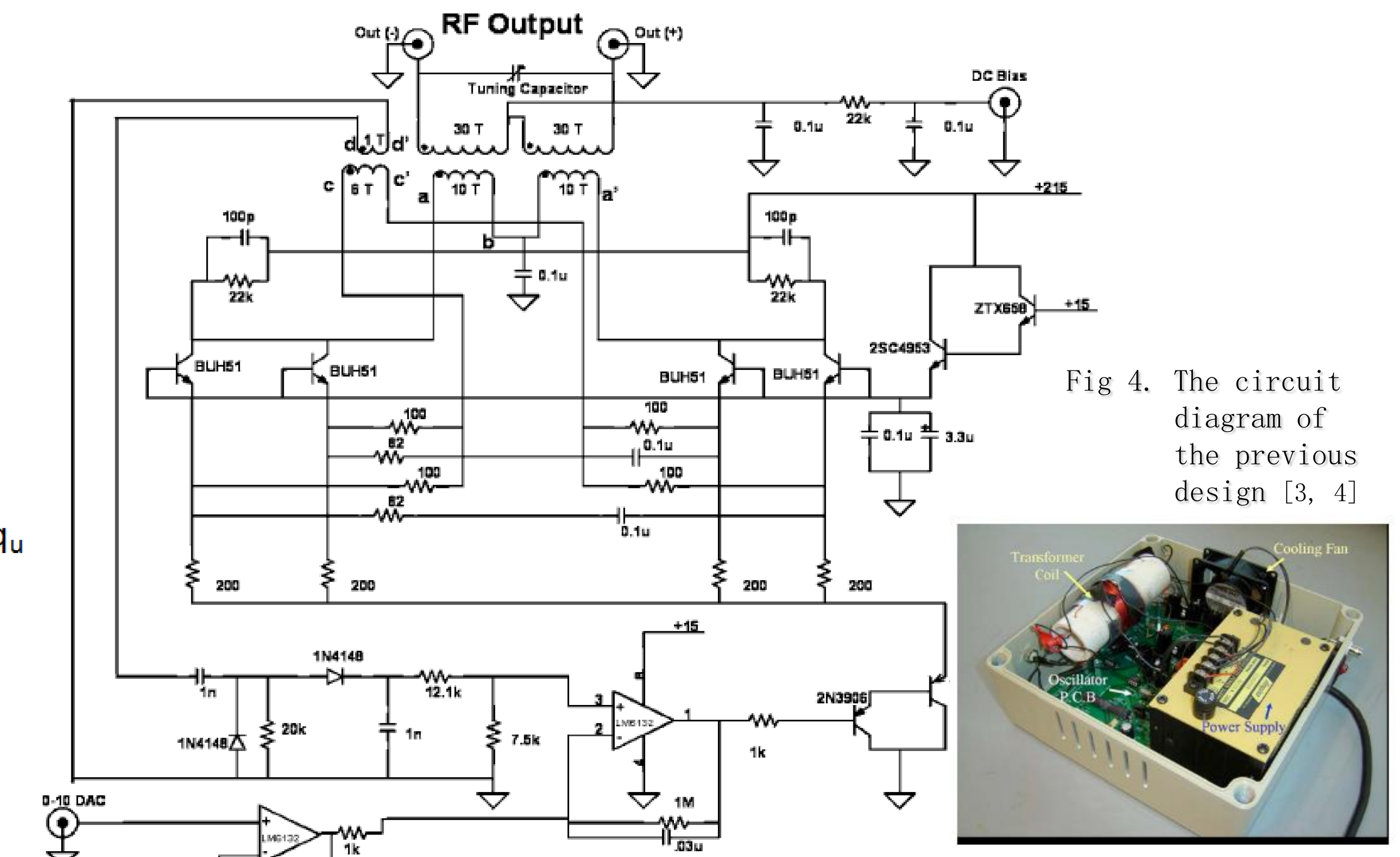

Fig 4. The circuit diagram of the previous design [3, 4]

- The previous design doesn't provide more than ~1% stability.

Modifications for Stability

Feedback coil feeds the output back to the emitters of the transistors in order to achieve oscillation condition.

The feedback network will be replaced by a crystal oscillator in order to stabilize the output frequency variation to a few tens of ppm.

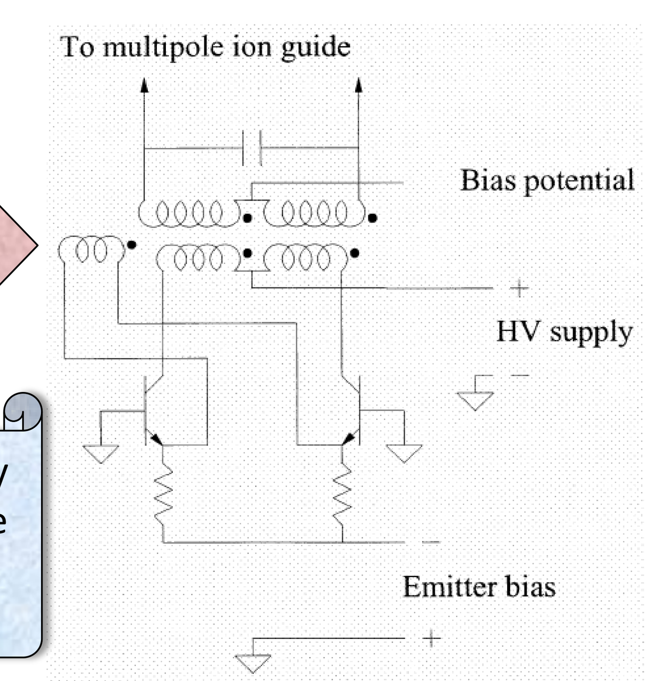

Fig 5. The oscillating circuit of the Fig 4 [3, 4]

In order to achieve 10^{-4} stability:

- Crystal Oscillator generates the reference waveform with solid frequency.
- Power Amplifier further amplifies the signal and transforms the output signal to multipole ion guides.
- Automatic Gain Control (AGC) will be built in to maintain the output amplitude.
- The Matching Network will be introduced between the circuit output and the multipoles.

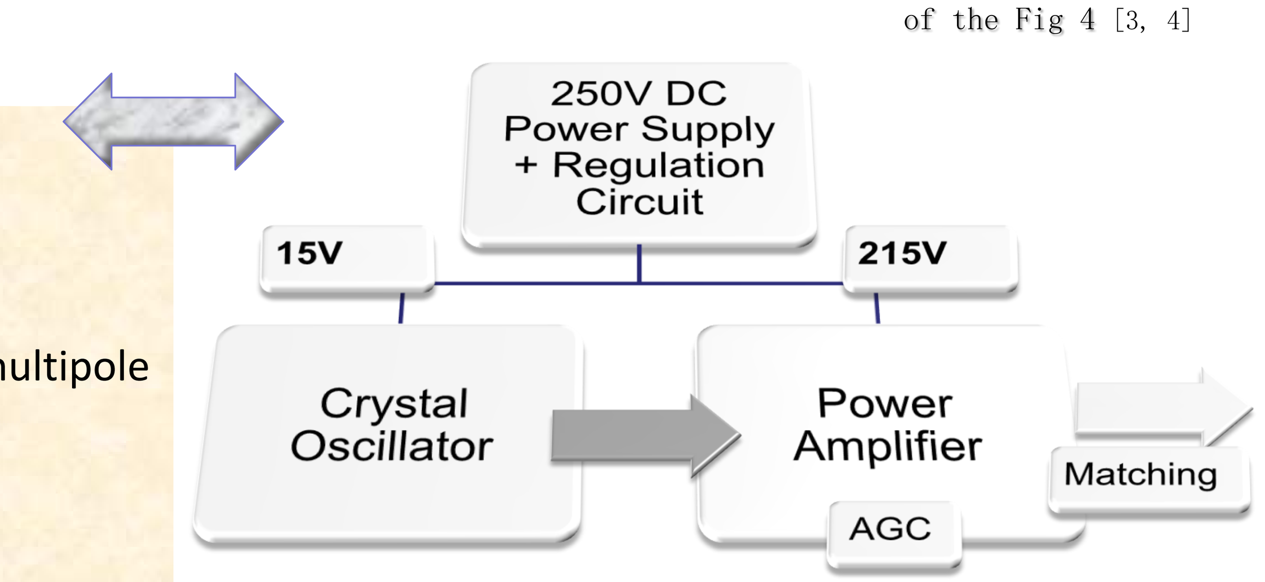

Fig 6. The building blocks for the new frequency stabilized oscillator

Simulation Results

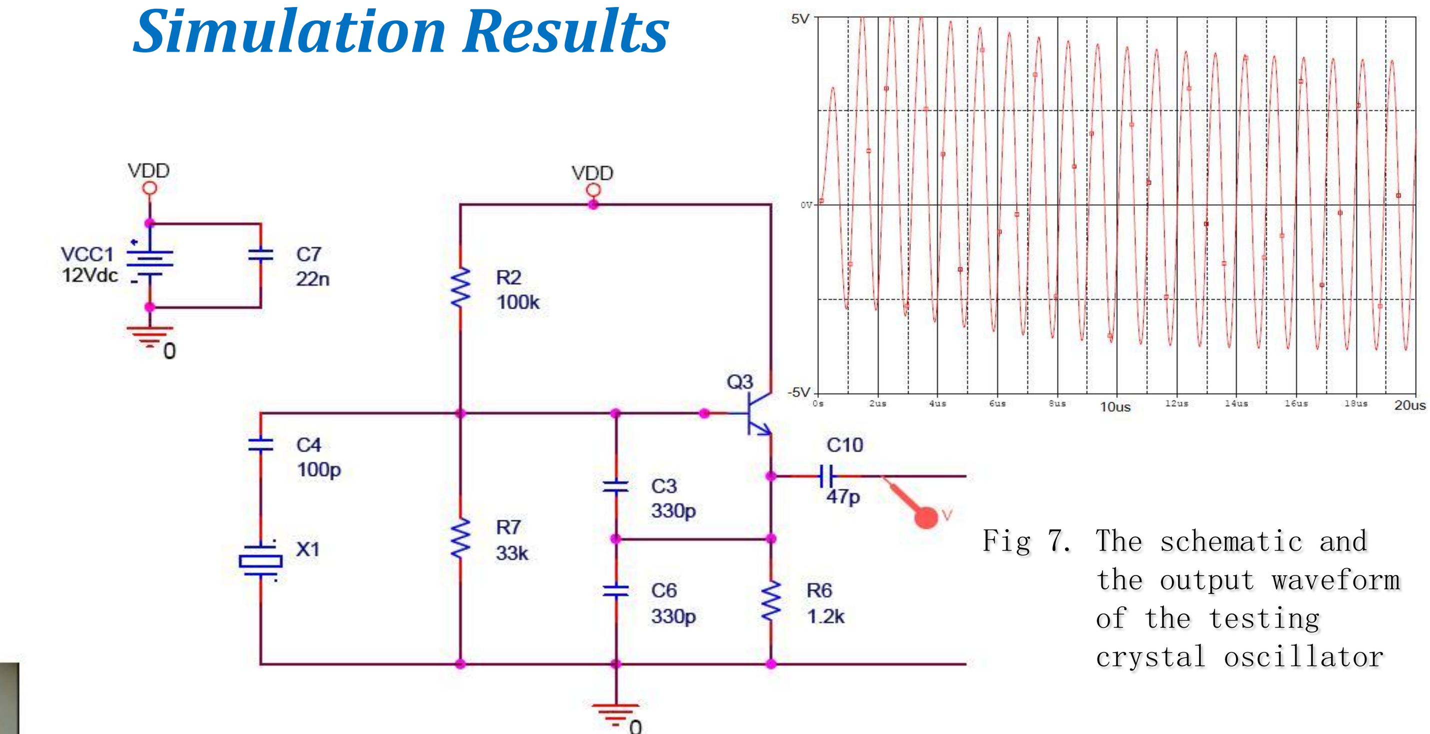

Fig 7. The schematic and the output waveform of the testing crystal oscillator

- A modified Colpitts crystal oscillator was tested for further modifications.
- The schematic in Fig 7 was implemented by transistor ZTX658 from ZETEX and crystal ECS-10-13-1H from ECS Inc to verify the Spice simulation.

Future Works

- To use the developed Spice models to verify new oscillator design ideas.
- To implement the new design and to verify the performance with the FT-ICR mass spectrometer.

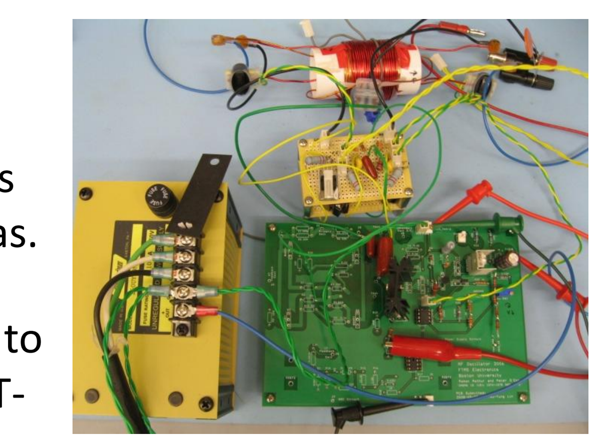

Fig 8. Testing circuits with 270V power supply

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