Upgrade the RF supply system for ISOLDE's laser ion source LIST

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Introduction

ISOLDE is one of the most longstanding active facilities in CERN. It has been operating successfully for over 50 years, excellent prospect awaits as it enters its second half-century. At ISOLDE, the idea of producing ion beams of radioactive isotopes became reality using the isotope on-line separator (ISOL) technique [1]. Among other parameters, the physical qualities of the ion beams produced strongly depend on the type of ion source used in the ionization process. The resonance ionization laser ion source (RILIS) is chosen for its high efficiency and selectiveness. RILIS uses step-wise atomic excitation by wavelength-tunable laser radiation [2]. A specialized RILIS variant, the laser ion source and trap (LIST), is utilized whenever high purity of an ion beam is essential [3].

ISOLDE and RILIS

The production of ion beams at ISOLDE starts with a nuclear reaction induced by 1.4GeV protons delivered from CERN Proton Synchrotron Booster accelerator to a thick target containing high z-material (as, e.g., uranium) which produces a variety of lighter radionuclides. The atomic vapor produced by the nuclear reaction and high temperature heating contains the isotope of interest alongside an enormous number of isobars [2]. A method of element selection is implemented so that the isotope of interest is ionized and extracted using the mass separator before it is delivered to the experimental stations. In RILIS, the isotope of interest is ionized by a step-by-step resonant excitation of atomic transitions with a wavelength-tuned laser radiation. Finally, in the last step, the electron is detached to form an ion. The laser wavelengths are precisely adjusted to match the successive electron transition energies of an ionization with the photon energies. Only the selected atomic species interacts with the laser radiation since every atomic element has a different electronic energy level structure. After acceleration, the created ion beam is then separated using a dipole magnet as mass separator [2].

LIST

Both element-purity and high efficiency is required at radioactive ion beam facilities such as ISOLDE. RILIS is chosen for its high efficiency and element-selectivity, however some isobaric contamination is generated making the beam less pure [2]. The laser ion source and trap (LIST) is an approach used whenever a pure ion beam is required. The LIST is constructed of a repeller electrode and a radio-frequency quadruple (RFQ) ion guide structure (see Fig. 1). High positive electric potential is applied to the repeller electrode to prevent any contamination by repelling the positive ions coming from the hot cavity and ensuring that only neutral atoms enter the RFQ ion guide structure [3]. Inside the ion guide structure, only the atoms of interest are ionized with RILIS laser. A traverse RFQ potential is used to confine the ions on the axis of the LIST to ensure minimal transport losses, the potential of the repeller electrode pushes the ions to the extraction hole, where multi-10kV acceleration for ion beam formation takes place. This mode of operation is called the *LIST mode*. Two other modes for the LIST are *ion guide mode* and the *PI-LIST mode*. In the ion guide mode, a negative potential is applied to the repeller electrode to extract the ions produced in the hot cavity and along the axis of the LIST. In this mode, the purity of the beam is substituted for higher efficiency [3]. In PI (Perpendicularly Illuminated)-LIST mode, a laser is introduced perpendicularly to greatly enhance spectral resolution for laser spectroscopy applications [4].

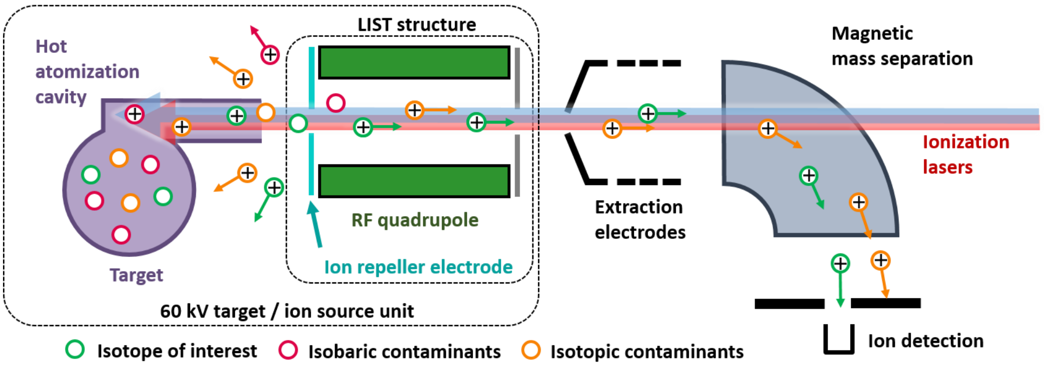


Figure (1): a schematic of the LIST as installed at ISOLDE

LIST RF supply system

The RF supply system provides the LIST RFQ unit with two high voltage, symmetrical RF signals. The RF setup is as follows; the sine wave RF frequency is generated by Tti TG2000 commercial generator. The limited power of the generator is compensated by the custom-built EAF081211 preamplifier [5]. The amplified signal then goes into the Transducer. The transducer is an LC resonant circuit that both amplifies and splits the incoming signal into two symmetrical ones with respect to ground (see Fig 2). The Transductor consists of an air-coil transformer with inductivity of approximately 38μH and three rotary capacitors, two long capacitors of 270pF and one short capacitor of 100pF. The signals are then delivered to the LIST rods by coaxial cables. An oscilloscope is used to monitor the signal in order to maximize the RF amplitude at the LIST by tuning the resonant frequency [5].

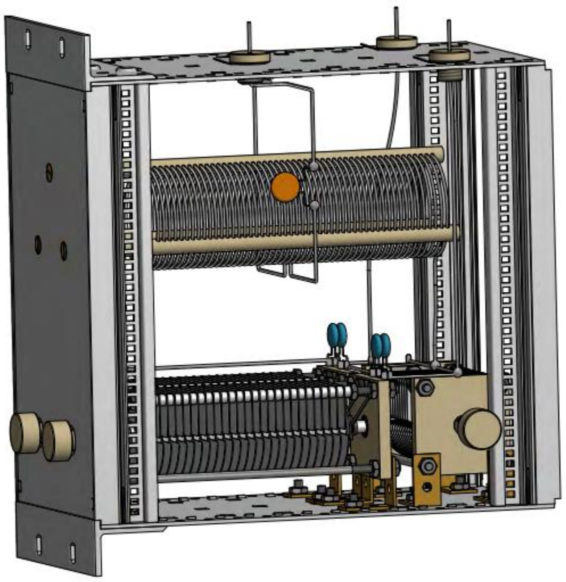


Figure (2): Transducer original design.

RF supply system upgrade goals

An upgrade to the transducer is necessary for multiple reasons. First, in the original design the transducer had to be radiation resistant, therefore all parts were custom made of metals, PEEK or other plastic which were certified by ISOLDE [5]. This feature is no longer needed, also these parts are not available anymore. Therefore, store available standard components will be used in the new design to make it cheaper, and easier to maintain. Second, the system setup has changed, two 20m long cables are now used after the transducer for transport of both phases to the LIST RFQ, adding a series capacitance of 2nF (100pF/m*20m) thus changing the performance of the transducer LC circuit. Also, the upgrade of the RF supply system includes two features. First, a DC offset option is required to shift the AC outputs. Second, a tuning option for the resonance frequency of the circuit is needed.

The relevance of RF upgrade to LIST applications

DC offset:

In the LIST mode previously discussed, a positive potential is applied to the repeller electrode, preventing ions from entering the RFQ ion guide structure and avoiding any contamination [3]. As the neutral atoms enters the RFQ ion guide structure, a cone shape for the atom's diffusion takes place meaning that the atoms density is the highest near the hot cavity and lowers as it moves into the LIST axis (see Fig. 3) [6]. After ionization by RILIS lasers the potential from the repeller electrode drifts the ions to the extraction hole. However, the potential ridge is almost 6 mm away from the hot cavity (see Fig 4). A DC offset will move the potential ridge closer to the hot cavity (denser area of the atoms) extracting more ions from the hot cavity to the extraction hole and improving the beam efficiency. Figure (5) shows the expected position of the potential ridge with a different value of the DC offset.

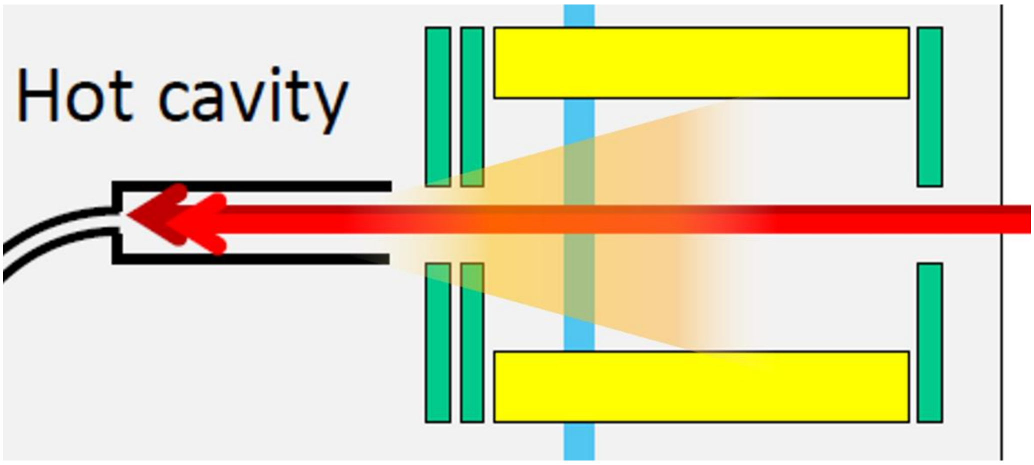


Figure (3): a schematic of the atom diffusion shape and the potential ridge placement.

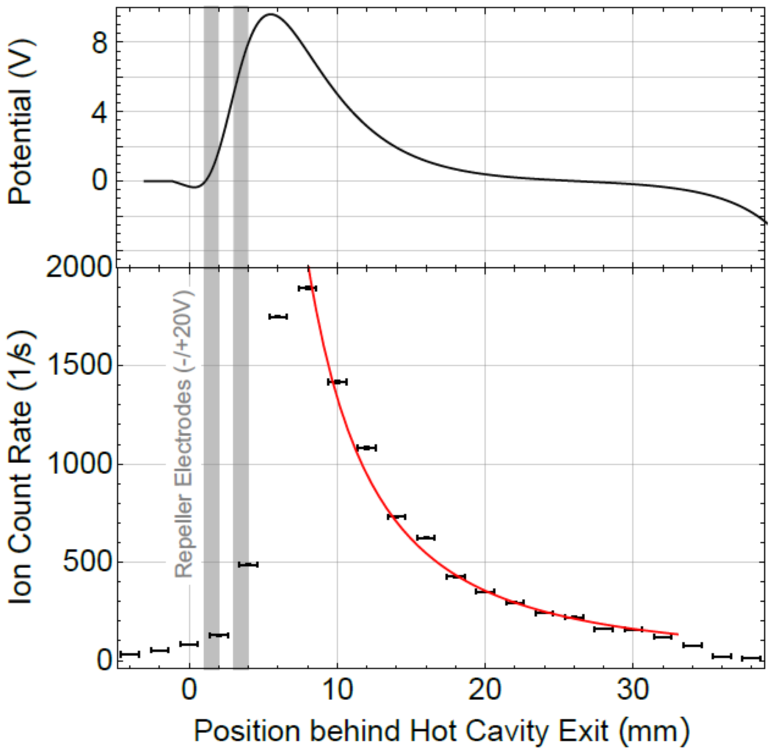


Figure (4): potential ridge position without DC offset. Figure taken from [6].

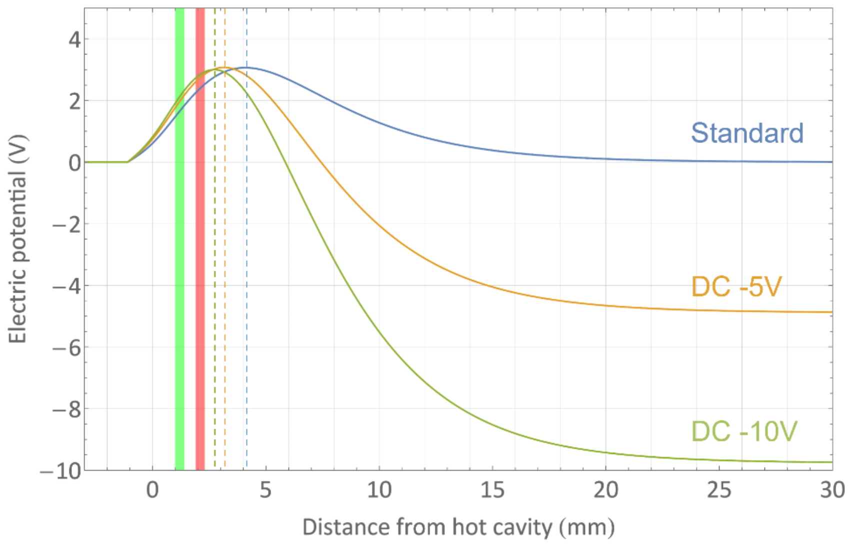


Figure (5): the expected position of the potential ridge with different DC offset.

Another benefit of the DC offset is seen in the LIST's ion guide mode. As mentioned before, the ion guide is used as a passage to transport through the RFQ structure; ions from the hot cavity as well as atoms ionized in the LIST axis [3]. The ion guide mode has higher efficiency than the LIST mode. Nonetheless the proper setting of the DC offset is expected to enhance this mode even more. In the classic mode (no DC offset) the repeller potential drifts the ions less than 20mm into the LIST axis, then as the potential fade the ions drift will fade, and fewer ions will reach the extraction hole (Fig 6). However, matching the repeller potential with a DC offset will continue the ion drift throughout the LIST axis and enhance the efficiency of this mode.

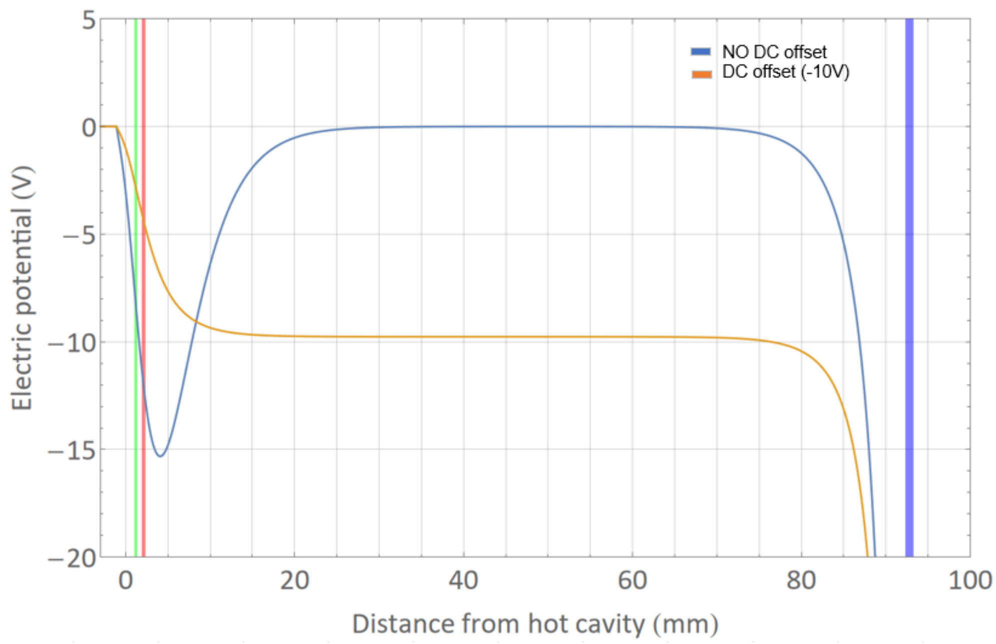


Figure (6): ion guide mode operating in different modes.

Resonance frequency:

The extraction efficiency and the ability to diminish the effect of surface ionization are the parameters by which ion source performance is determined. Research at the ISOL facility at TRIUMF with its LIST-type ion source IG-LIS (ion guide laser ion source) shows that different extraction rates can be reached by set of frequencies for different ion beams. The test is done on an Al beam from a SiC target during an on-line run. Figure (7) shows the Al extraction rate as a function of RF amplitude and frequency with comparison to simulated transmissions at 1MHz [7].

Keeping in mind that the geometry for the LIST used in ISOLDE is different than the one of IG-LIS used at TRIUMF and could be more dependent on the proper setting of the RF frequency, the feature of tunable resonant frequency will enable us to test a different set of frequencies and concludes the best transmission rate for different ion beams.

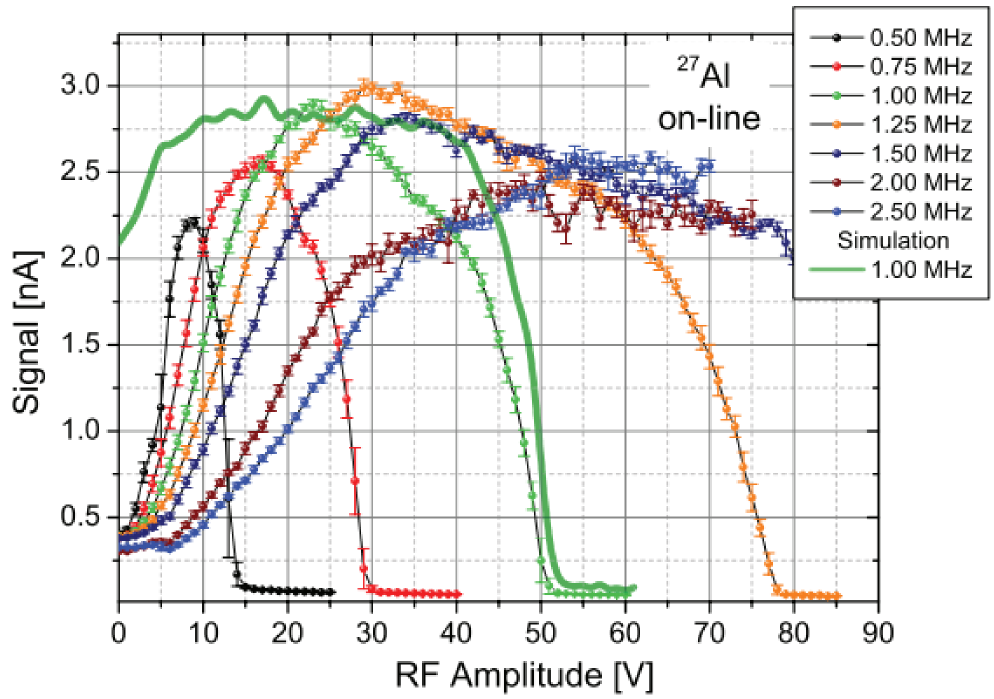


Figure (7): transmission rate for Al ion beam as a function of RF amplitude and frequency. Figure taken from [7]

DC offset design

The DC offset design was accomplished by capacitive coupling of AC signal into DC supply. The DC design included two 10μF non-polarized capacitor configured to separate the AC and DC components. Capacitor (C1 in Fig. 12), is a coupling capacitor which passes the AC signal with minimal attenuation (since it has low impedance $Z = 1/(j\omega C)$) while preventing the DC offset. The AC signal will be a varying voltage level around the DC offset. Capacitor (C13 in Fig. 12) acts as a bypass or a decoupling capacitor that provides any remaining AC signal with a low impedance path to the ground thus ensuring that no AC signal will enter the voltage source or effect the DC offset. The value of 10μF was chosen to accommodate the high voltage needed in the setup. Also, high resistors of 0.940MΩ were used to prevent leakage of the AC signal into the DC supply. The values of the resistor were carefully chosen to avoid creating voltage divider circuit knowing that the oscilloscope has input impedance of 1MΩ and the 10x probe used to monitor the final setup has input impedance of 10MΩ.

As expected, simulating the DC offset using oscilloscope input will produce a DC offset of half the DC voltage applied. However, with 10x probe almost full DC offset will be created. In figure (8), we can see the final design of the DC box. At the top left jack comes the AC output of the transducer, at bottom jack comes the DC supply and at the top right jack is the AC output accompanied by the DC offset.

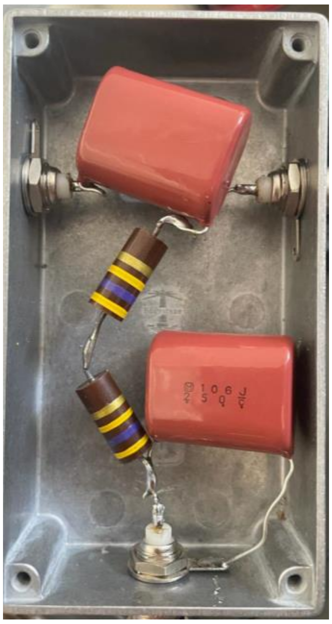


Figure (8): DC box

Design for tenable resonance frequencies

In the original design of the transducer the resonance frequency is fixed to 1180kHz without long cables, and 707kHz with 20m long cables connected to each output of the transducer (the new setup). As seen from the graphs in figure (9), the added capacitance of the cables lowered the resonance frequency. Keeping in mind that this data only considers the resonance frequency of the original design not the maximum voltage that could be achieved. The goal for the upgraded design of the transducer is to make the resonance frequency tunable to a range of 0.5 – 2MHz while keeping the voltage amplitude at 200Vp-p.

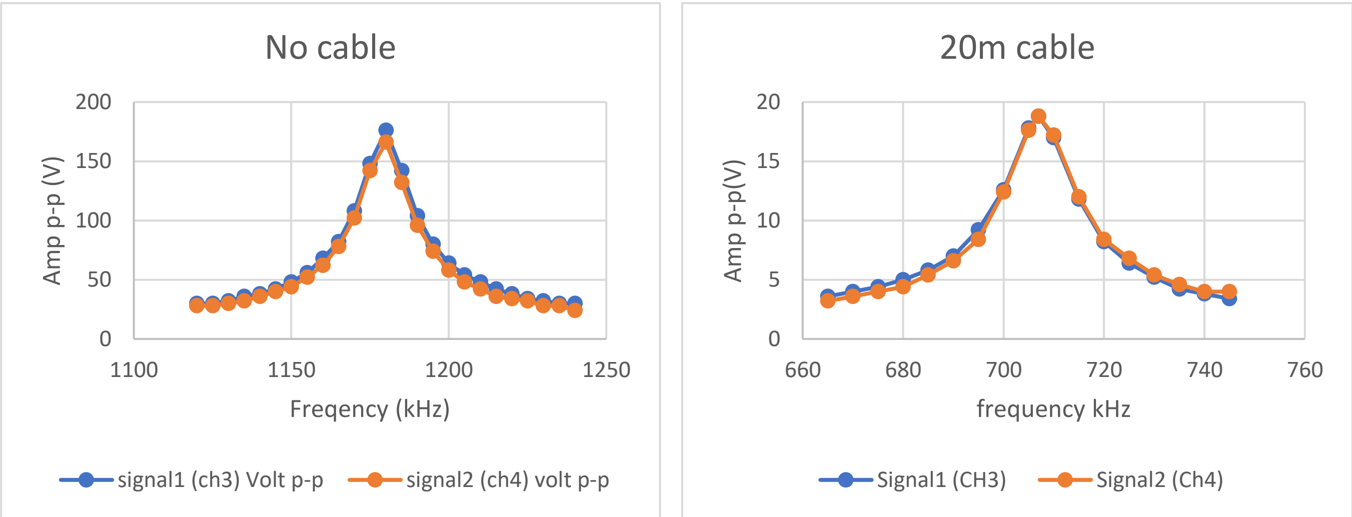


Figure (9): the result of the original design of the transducer.

In order to achieve that, different designs were tested to find the balance between the resonance frequency and the voltage amplitude. The designs tested included different values of the transformer inductance and the capacitance of the variable capacitor. Keeping in mind that the plan is to first increase the resonance frequency as much as possible while keeping the voltage amplitude at 200Vp-p. After that, a capacitor parallel to the outputs of the transducer is added to take the resonance frequency back to low values.

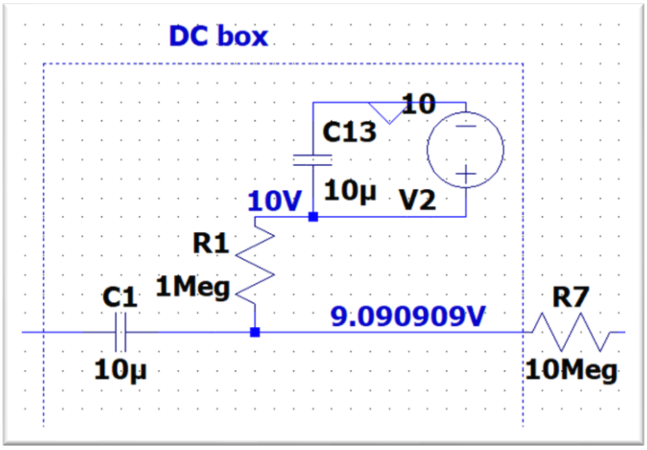
Before purchasing the component and building the final design, a mockup design was created from the original transducer, since the Ltspice simulation did not give accurate results (see discussion below). The mockup design was created by resoldering the transformer wires to reduce the number of active windings of the coil and therefore reducing the inductance, taking out the plates of the variable capacitors to reduce their capacitance, and soldering a non-polar capacitor parallel to the outputs of the transducer. Figure 10 shows the final mockup design while figure 11 shows the connection of the 3nF parallel capacitor. Also, a schematic of the final design in seen in 14 where the parallel capacitor is represented as C7. The values for the mockup design were 5.5µH for the transformer, 44pF for the variable capacitor for each output of the transducer and for the parallel capacitor a set of values were used. With no parallel capacitor, the maximum resonance frequency is reached at 1.208MHz, the values of 1.12nF, 3.04nF, 5.6nF gave 0.906MHz, 0.670MHz, and 0.530MHZ resonance frequency respectively.

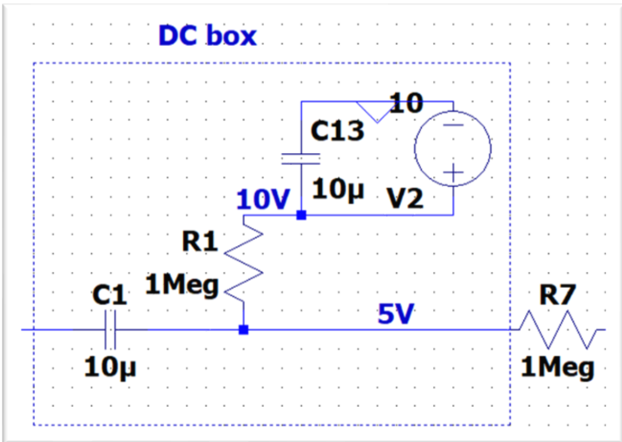
Figure (10): mockup design designed to test different resonance frequencies.

Figure (11): parallel capacitor connection in the mockup design

Result and discussion

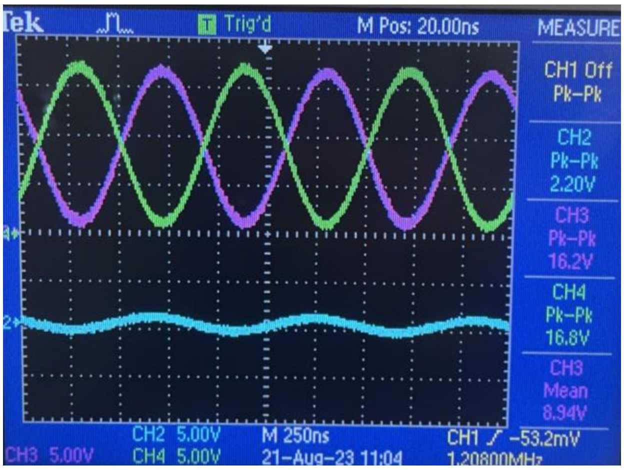
As we can see in the figures below the experimental outcome of the DC box supported the LTspice simulation which were consistent with our expectations. Depending on the resistance of the monitoring tool different DC offset is obtained, as discussed previously. The preferred method is to use 10x probe while monitoring the DC offset.

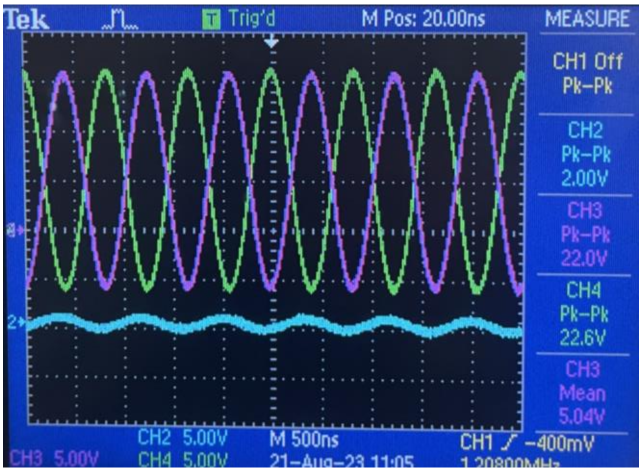




(a) simulation using 10x probe (b) simulation using oscilloscope input

Figure (12): Ltspice simulation of DC box





(a) simulation using 10x probe (b) simulation using oscilloscope input

Figure (13) DC box measured by oscilloscope.

The Ltspice simulation of the final design included the DC box, the 10x probe used for monitoring and the long cables used in the setup. For the 20m, 50Ω, RG58 cable with velocity ratio of 66% the speed of light, the delay time is calculated to be 101ns

$$Td = \frac{length}{propogation\ speed}\ ,\ \ propogation\ delay = C * velocity\ ratio.$$

The simulated results shown below (Fig. 14) displayed a limited degree of similarity to the experimental result in figure (15). Different reasons were tested to explain the limited resemblence. First, the cable electrical length is not quarter wave the resonance frequency $\lambda = C/f$. Second, the wavelength of the resonant frequency is many times greater than the delay imposed by the cable since if that happened it could imposed a driving impedance on the left side of the circuit that would be significantly different than the right side. The most likley reasons for the limited similarity is that a change in the inductance and capacitance of the circuit alterd the Q-factor of the circuit. Also, an unintentuinal capacitance of the variable capaitor plates or the air-coil winding (parasitic capacitance) could affect the resonance frequency of the circuit since in any resonance circuit the resonance frequency is achieved when the capacitance and inductance of the element cancel each other leaving a purly resistive circuit. However, the parasitic capacitince might alter the preformance of the circuit by increasing the capacitance and lowering the resonance frequency. Finally, the Tline component in the simulation models a losseless transmission line. However, for more accurate simulation of the cables a more advanced simulation tool could be used such as (ADS) or a model of short transmission line could be drawn.

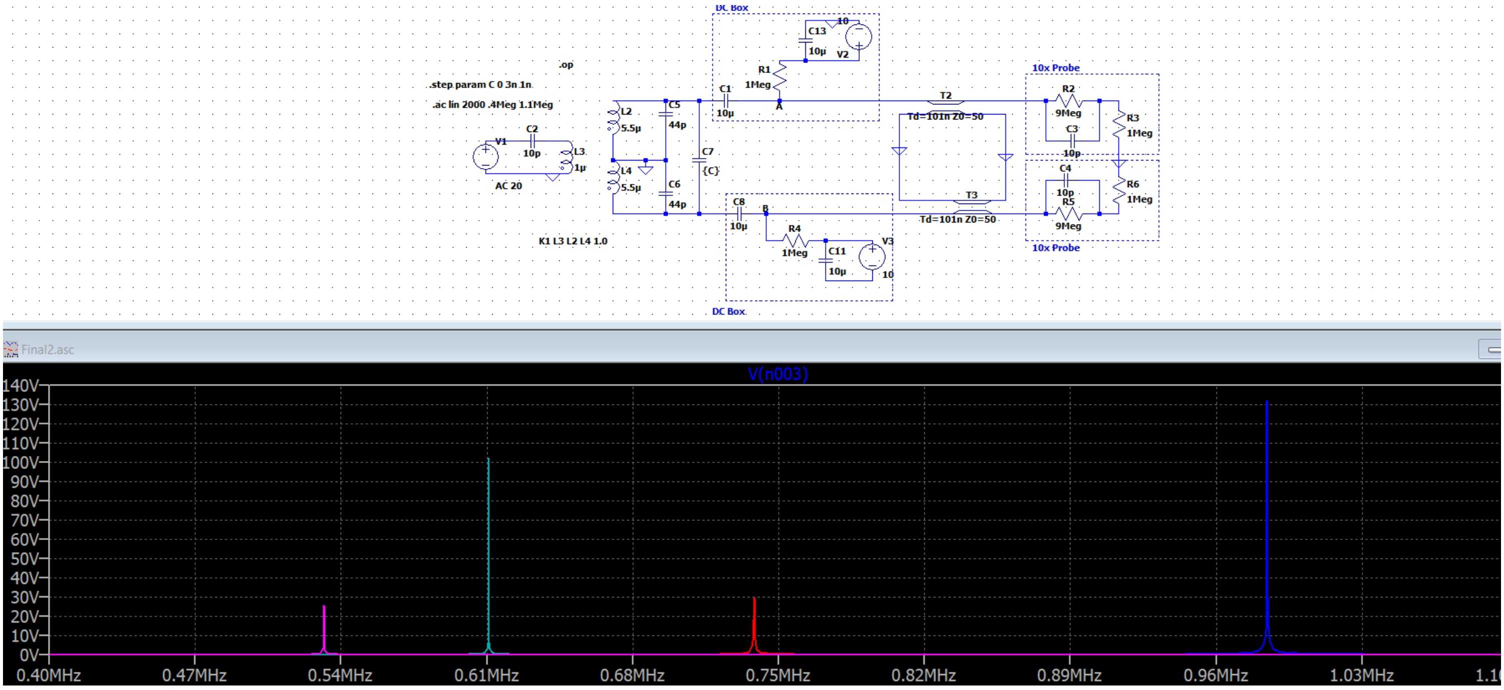


Figure (14): Ltspice simulation to final design of the transducer

The final design showed promising results since a range of resonance frequencies were obtained using a set of values for the parallel capacitor. As seen in Fig.15, by changing the value of the parallel capacitor we can control the resonance frequency of the circuit while still achieving the desired amplitude of 200 Vpp with proper settings of the pre-amplifier. Now, a PCB prototype for the upgraded RF supply system can be built using the final design and values of the transducer, and a design for easier manufacturing be finalized, including the new possibilities for DC offset and (potentially remote-controllable) frequency tunability.

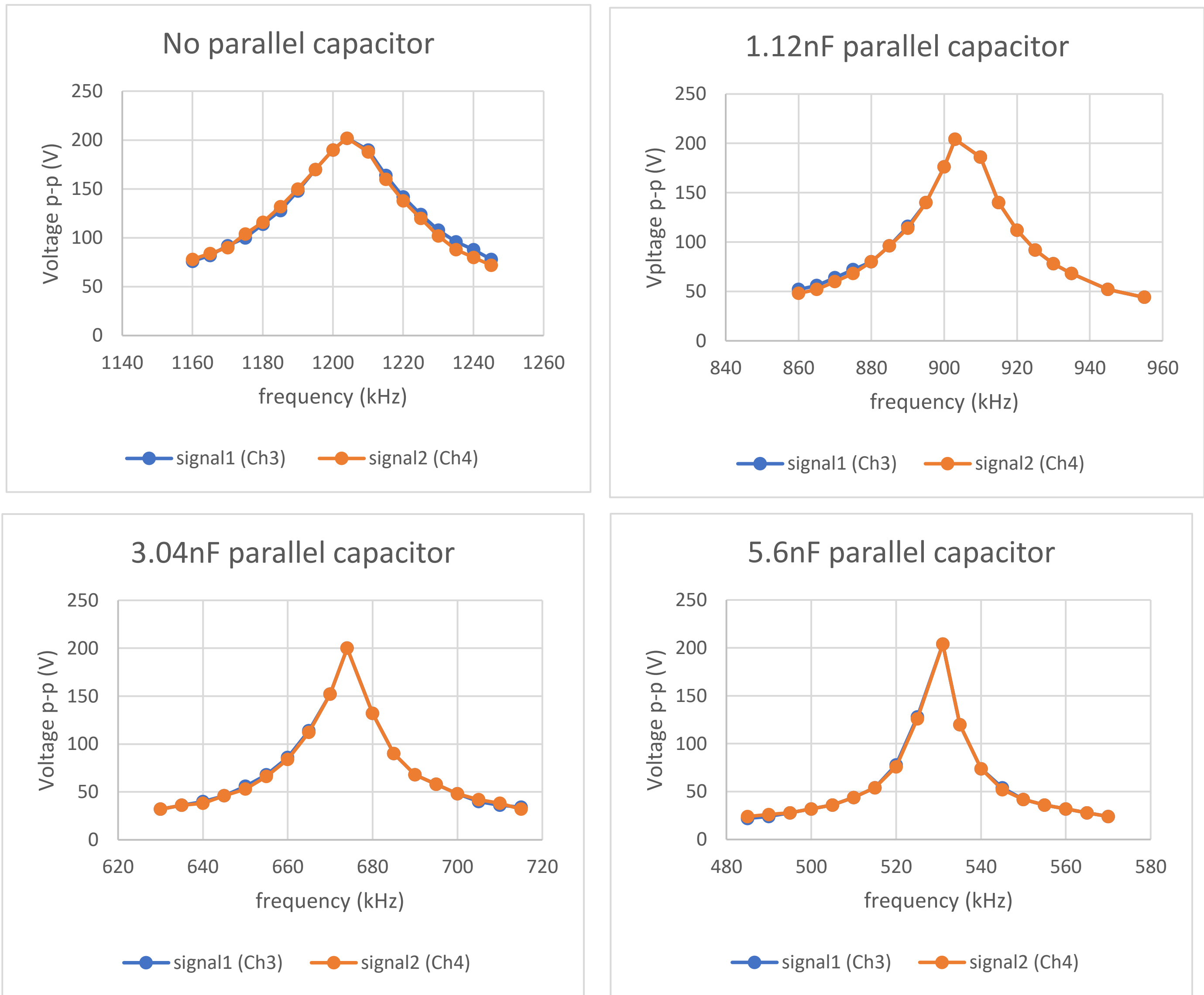


Figure (15): experimental result for resonance frequencies for a set of parallel capacitors (C7 in Fig. 13).

References

[1] M. J. G. Borge and B. Jonson, “ISOLDE past, present and future,” IOPSCIENCE, 9 March 2017.

[2] V. Fedosseev, K. Chrysalidis, T. D. Goodacre, B. Marsh, S. Rothe, C. Seiffert and K. Wendt, “Ion beam production and study of radioactive isotopes with the laser ion source at ISOLDE,” IOPSCIENCE, 2017.

[3] D. A. Fink, S. D. Richter, K. Blaum, R. Catherall, B. Crepieux, V.N. Fedosseev, A. Gottberg, T. Kron, B. A. Marsh, C. Mattolat, S. Raeder, R.E. Rossel, S. Rothe, F. Schwellnus, M.D. Seliverstov, M. Sjödin, T. Stora, P. Suominen, K.D.A. Wendt,, “On-line implementation and first operation of the Laser Ion Source,” Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,, 2015.

[4] R. Heinke, M. Au, C. Bernerd, K. Chrysalidis, T. E. Cocolios, V. N. Fedosseev, I. Hendriks, A. A.H. Jaradat, M. Kaja, T. Kieck, T. Kron, R. Mancheva, B. A. Marsh, S. Marzari, S. Raeder, S. Rothe, D. Studer, F. Weber, K. Wendt,, “First on-line application of the high-resolution spectroscopy laser ion source PI-LIST at ISOLDE,” Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions With Materials and Atoms, 2023.

[5] S. Richter, “LIST construction,” Johannes-Gutenberg Universit¨at Mainz, 2014.

[6] R. Heinke, V. Fedosseev, T. Kieck, T. Kron, B. Marsh, S. Raeder, S. Richter, S. Rothe, K. Wendt, “Atom beam emersion from hot cavity laser ion sources,” Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions With Materials and Atoms, 2020.

[7] S. Raeder, H. Heggen, J. Lassen, F. Ames, D. Bishop, P. Bricault and P. Kunz, “An ion guide laser ion source for isobar-suppressed rare,” AIP publishing, 2014.