Abstract: The resonant circuit in an Inductive Output Tube (IOT) extracts the kinetic energy of the modulated electron beam converting it to electromagnetic energy. For the application considered here, mobile low-frequency sources (5-10 MHz) for ionospheric heating, high efficiency is important, and thus class D operation is desired. The broad frequency range requires the circuit to be tunable, and the need for a constant decelerating voltage requires constant impedance. This paper discusses the design and construction of a resonant circuit with a highly coupled transformer that has the above features. The design and optimization of the circuit was performed with Orcad Spice and the transformer design was designed using Cadence Autodesk Inventor and a finite element electromagnetic field solver, Maxwell 3D and HFSS Simulator software.

Keywords: Inductive Output Tube; Resonant Circuit; Radio Frequency; Tank Circuit; Transformer; Constant Impedance.

Introduction
An Inductive Output Tube [1, 2] achieves high efficiency by utilizing a density-modulated beam that passes through a decelerating gap supporting an RF voltage. High efficiency is achieved when all beam electrons pass through the gap during the decelerating phase of the RF, thus achieving uniform energy transfer from the beam to the RF. The RF field is supported by a resonant circuit, or cavity, that restricts the frequency of operation. Due to the high harmonic content of the beam current, the resonant circuit should have a relatively high quality factor (Q ~ 5-50) to suppress harmonic voltages. Further, for the application considered here, development of a mobile source for ionospheric heating [3], the frequency of operation should be tunable in the range 5-10 MHz. These requirements necessitate using a variable-frequency resonant circuit. As the resonant frequency of the circuit is varied, its impedance should remain roughly constant so that beam electrons are fully decelerated at all frequencies. We describe here the design and testing of such a circuit.

The constant impedance resonant circuit design discussed in this paper is shown in Fig. 1. It utilizes a highly coupled transformer, the primary of which is connected to the gap in the beam tunnel, through which the beam passes and which adds a small capacitance in parallel with the primary. The secondary of the transformer is connected to the parallel combination of a capacitor \( C_s \) and a transmission line of characteristic impedance \( R_0 \). To characterize this circuit we first assume that the transformer is lossless \((R_1 = R_2 = 0)\) and perfectly coupled with inductance matrix elements \( L_{pp} = N^2 L_o \), \( L_{ss} = M^2 L_o \), and \( L_{ps} = L_{sp} = NM L_o \), where \( p \) and \( s \) refer to the primary and the secondary, \( N \) and \( M \) are the number of turns in the primary and secondary \( L_o \) is the turn per inductance. Associated with the primary is a total capacitance \( C_p \). For this simple circuit the admittance seen by the beam current can be written as,

\[
Y_p(\omega) = Y_o + jB \left( \frac{\omega_o}{\omega} - \frac{\omega_o}{\omega} \right) \equiv Z_{gap}^{-1}
\]

where \( \omega_o = 1/\sqrt{L_o(N^2C_p + M^2C_s)} \) is the resonant frequency, \( B = \sqrt{L_o(N^2C_p + M^2C_s)/N^2L_o} \) is a circuit reactance and \( Y_o^{-1} = N^2R_o/M^2 \) is the resistance seen by the beam at resonance. From Eq. (1) we see the quality factor for this circuit is \( Q = 2B/Y_o \). The admittance as seen by the beam is the inverse of impedance also called gap impedance as shown in (1).

The circuit can be tuned by varying either the primary or secondary capacitance. When this is done the impedance at resonance (resistance) presented to the beam is \( Y_o^{-1} = N^2R_o/M^2 \) which depends only on the ratio of turns and the characteristic impedance of the transmission line, i.e. it is independent of frequency. The quality factor does vary moderately (by a factor of 2) as the resonant frequency is changed.

The constant impedance resonant circuit design discussed in this paper is shown in Fig. 1. It utilizes a highly coupled transformer, the primary of which is connected to the gap in the beam tunnel, through which the beam passes and which adds a small capacitance in parallel with the primary. The secondary of the transformer is connected to the parallel combination of a capacitor \( C_s \) and a transmission line of characteristic impedance \( R_0 \). To characterize this circuit we first assume that the transformer is lossless \((R_1 = R_2 = 0)\) and perfectly coupled with inductance matrix elements \( L_{pp} = N^2 L_o \), \( L_{ss} = M^2 L_o \), and \( L_{ps} = L_{sp} = NM L_o \), where \( p \) and \( s \) refer to the primary and the secondary, \( N \) and \( M \) are the number of turns in the primary and secondary \( L_o \) is the turn per inductance. Associated with the primary is a total capacitance \( C_p \). For this simple circuit the admittance seen by the beam current can be written as,

\[
Y_p(\omega) = Y_o + jB \left( \frac{\omega_o}{\omega} - \frac{\omega_o}{\omega} \right) \equiv Z_{gap}^{-1}
\]

where \( \omega_o = 1/\sqrt{L_o(N^2C_p + M^2C_s)} \) is the resonant frequency, \( B = \sqrt{L_o(N^2C_p + M^2C_s)/N^2L_o} \) is a circuit reactance and \( Y_o^{-1} = N^2R_o/M^2 \) is the resistance seen by the beam at resonance. From Eq. (1) we see the quality factor for this circuit is \( Q = 2B/Y_o \). The admittance as seen by the beam is the inverse of impedance also called gap impedance as shown in (1).

The circuit can be tuned by varying either the primary or secondary capacitance. When this is done the impedance at resonance (resistance) presented to the beam is \( Y_o^{-1} = N^2R_o/M^2 \) which depends only on the ratio of turns and the characteristic impedance of the transmission line, i.e. it is independent of frequency. The quality factor does vary moderately (by a factor of 2) as the resonant frequency is changed.
Design Parameters
We select parameters appropriate for a beam produced by the gun in Ref. 4 with anticipated beam energy of 70 kV and peak beam current 15 A in 25% duty cycle, 5 MHz pulses. In this case the beam current has a fundamental frequency component of 6.75 A. Expression (1) based on a simple model has been refined [3, 5] to include series resistance in the transformer turns and less than perfect coupling. Using the refined model, we select a target gap impedance $Z_{gap}$ of 9.8 kΩ to decelerate the beam by, 66 kV. This can be matched to an output transmission line of 50 Ω if the turns ratio $N/M = 14:1$. Further, we select the primary inductance $L_{pp}$ and secondary inductance ($L_{ss}$) to be 23.49 µH and 0.249 µH respectively. Primary capacitance will be chosen to determine the variable resonant frequency. Given that the other parameters are fixed the quality factor will vary as the resonant frequency varies. A plot of the magnitude of the gap impedance $Z_{gap}$ versus frequency using the above parameters and varying resonant frequencies is shown in Fig. 2a. Tunability is achieved by varying the primary capacitance ($C_p$) from 1.07 nF to 10.78 pF. Fig. 2(a) confirms the relative constancy of the peak gap impedance as the resonant frequency is varied, while there is also an expected decrease in quality factor as resonant frequency increases.

Transformer Model and Simulation
In order to ensure that the power coupling is extremely efficient, we designed and are in the process of constructing a prototype transformer with a high coupling coefficient. A toroidal, air core transformer was chosen as it minimizes flux leakage and losses. The coupling coefficient is dependent on the portion of total flux lines captured by both the primary and secondary windings. Ideally, all the flux lines generated by the primary should cut the secondary, and all the lines of the flux generated by the secondary should cut the primary. The coefficient of coupling would then be unity, as required for constant impedance. The toroidal transformer model designed on Cadence Autodesk [7] and imported to Maxwell [8] is as shown Fig. 2(b). The coupling coefficient for this design is only 0.47 and efforts are being made to increase this value by considering designs with multiple secondary coils.

Summary
A preliminary design of the variable frequency extraction circuit has been presented here. At the conference, simulation results and additional measurements of a fabricated circuit will be presented.

Acknowledgements
This work is supported by the Air Force Office of Scientific Research under grant FA95501410019.

References
1. R. Seviour, ‘Comparative Overview of Inductive Output Tubes,’ ESS report, June 2012.
7. Autodesk® Inventor 2016