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Characterization of Inductive loop coupling in a Cyclotron Dee Structure

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Abstract

Many of today's low to medium-energy cyclotrons apply RF power to the resonator structure (the dees) by inductive loop coupling through a feed-line driven by an RF transmitter employing a triode or tetrode power tube. The transmitter's output network transforms the tube's optimum load line (typically a few thousand ohms) down to Z_0, typically 50 ohms. But the load-line is not a physical resistance, so one would not expect to see 50 ohms when looking back toward the transmitter. Moreover, if both the resonator's input and the transmitter's output are matched to Z_0, then the coupled or working Q of the resonator is reduced to half that of the uncoupled Q, implying that half the power is being dissipated in the transmitter's output resistance- an inefficient and expensive solution for a high power RF application. More power is available if the transmitter's reverse-impedance is not matched to Z_0, but this may result in misalignment between the frequency for correct forward match at the loop, versus the frequency for maximum power in the resonator. The misalignment can be eliminated, and the working Q maximized, by choosing the appropriate length of feed-line between the non-matched transmitter output and the matched resonator's input. In addition, the transmitter's output impedance may be complex, comprising resistance plus reactance, requiring a further process and means of measuring the output impedance so that an additional compensating length of feed-line can be incorporated. But a wrong choice of overall feed-line length- even though correctly load-matched at the resonator's operating frequency- can result in a curious degenerate condition, where the resonator's working Q appears to collapse, and the potential for transmitter overload increases substantially: a condition to be avoided!

Keywords: Impedance matching; RF power transfer; Q-Circle; Smith Chart, wide-band, degenerate condition

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1.0 Introduction

We'll first present a general formula for z_{in}, the normalized impedance looking into the loop, which will facilitate exploration of the relevant parameter space without regard to specific component values or frequency range. We'll find that the normalized reactance of the isolated coupling loop x_{L1} is of singular importance in the characterization and understanding of overall RF System properties and performance. Setting $z_{in} = 1.0$, i.e., forcing a matched condition, and solving for the real and imaginary parts of the resulting equation, reveals useful inter-relationships between resonator parameters. A further transformation, mapping the z-plane onto the unit circle, yields the complex reflection coefficient, Γ, resulting in the familiar *Smith Chart* representation by which we can plot Γ over a wide enough frequency range to produce a geometric construct called a Q circle, which greatly facilitates visualization of the effects of varying parameters such as resonator Q, coupling and loop reactance, etc..

Transporting the Q circle upstream, away from the load and toward the transmitter through an appropriately chosen length of transmission feed-line allows us to align the axis of the Q circle with the real (resistance) axis of the Smith Chart, thereby revealing a method and formula for estimating the complex output impedance of the transmitter which, in turn, guides the choice of overall resonator-plus-generator feed-line length required to align the frequency for best z_0 match with that for maximum power in the resonator. RF simulation software [Harriman, 2015], combined with 'hands-on' measurements on a High-Q model resonator using a Vector Network Analyzer [SDR kits 2017] provides validation for the results presented.

2.0 Resonator Input Impedance

Near resonance, the cyclotron Dee structure can be modelled as an equivalent lumped circuit. From standard circuit analysis:

$$Z_{in} = V_{in} / I_{in} = j\omega L_1 + \{\omega^2 M^2\} / \{j[\omega L_2 - 1/\omega C] + R\} \quad (1)$$

Adroit manipulation of terms and changes of variable yield a more compact and general formula which is independent of any specific frequency range or specific component values (see Appendix A for derivation):

$$z_{in} = jx_{L1} + (k^2 Q_0\, x_{L1}) / (1 + j\psi) \quad (2)$$

where $\mathbf{z_{in}}$ (lower case) is the normalized impedance with respect to Z_0 (50 ohms) measured directly at the loop's input terminal; $\mathbf{x_{L1}}$ is the normalized self-reactance of the loop– assumed constant near resonance; **k** is the inductive coupling coefficient between loop L_1, and dee stem L_2; $\mathbf{Q_0}$ is the un-coupled Q of the resonator = ω_0 / (bandwidth); $\boldsymbol{\psi} = (\omega-\omega_0) / (\omega_0 / 2Q_0)$ is a generalized frequency variable expressed as a number of half- bandwidths displaced from ω_0, the natural resonant frequency of the un-coupled resonator.

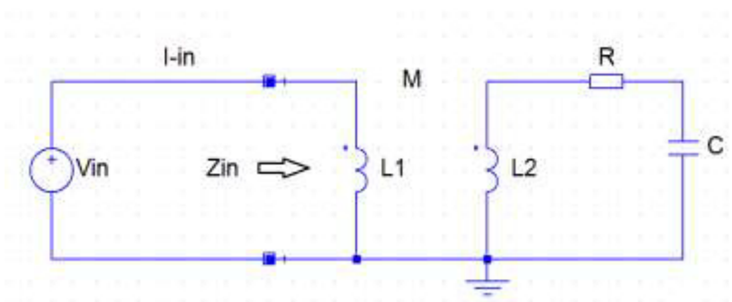

Fig. 1 Equivalent lumped circuit.