# CONCEPT OF THE DETUNED PRIMARY COUPLING AND MODEL MEASUREMENTS FOR THE RADIOFREQUENCY SYSTEM OF THE VINCY CYCLOTRON

B. BOJOVIĆ

*Vinča Institute of Nuclear Sciences, P. O. Box 522, 11001 Belgrade, Yugoslavia*

A. SUSINI

*CERN, 1211 Geneva 23, Switzerland*

A new concept of the impedance matching of a radiofrequency (RF) amplifier (primary) coupled to a cyclotron RF cavity (secondary) is discussed. In this arrangement the necessity of moving the coupling loop in vacuum is avoided, and the impedance matching for different operating frequencies is performed only by a variable capacitor. A design procedure based on the transformer equations is proposed, and the design of the RF system of the VINCY Cyclotron, the main part of the TESLA Accelerator Installation, based on the concept of the detuned primary coupling is presented. The measurements on a 1:1 scale model of the RF system of the VINCY Cyclotron were carried out for the whole range of the operating frequencies. The results obtained confirmed the viability of the coupling concept for the cyclotron RF systems.

## 1 Introduction

The conventional method for power transfer from the amplifier to the cavity is with a 50 Ω feeder line coupled to the cavity by an inductive loop. For variable frequency cyclotrons, two coupling parameters have to be adjusted for different frequencies: the impedance matching between the feeder line and the coupling loop and the loop coupling factor. The impedance matching is generally attained with a variable capacitor in series with the loop. The use of such capacitor can be avoided by the use of resonant coupling [1]. Instead of impedance matching on both sides of the 50 Ω feeder line, the anode circuit is made resonant, i.e. the amplifier cabinet together with the coupling loop and a transmission line connecting them forms a λ/4 or λ/2 resonator, reducing the impedance matching to one tuning element - a parallel capacitor in the anode circuit.

The movement of sliding short (or any other frequency tuning device) in variable frequency RF cavities changes the position of the coupling loop relative to the short circuited end of the cavity, thus changing the coupling factor of the loop. This change has to be compensated in order to establish the desired voltage ratio between the dee and the anode. This is performed either by turning the loop relative to the direction of the magnetic field in the cavity, or by changing the loop penetration depth [2]. Both ways require a motion in vacuum close to the vacuum window of the coupling line. The friction of the moving surfaces increase the sputtering of materials on the vacuum side of the insulator of the vacuum window, leading to electrical discharges over the insulator. These discharges, causing a high danger of breaking the insulator, together with construction constraints of the moving mechanism, make this insulator one of the weakest points of a variable frequency cyclotron cavity [3].

In this paper we propose a resonant coupling system with "detuned primary coupling" [4,5]. The position of the coupling loop is fixed, and the desired dee-to-anode voltage ratio is achieved by detuning the eigenfrequency of the amplifier cabinet (primary) relative to the eigenfrequency of the resonant cavity (secondary), without changing the coupling factor. The use of a static coupling loop avoids the use of any moving elements in vacuum and eliminates all the design and operational drawbacks of the conventional solution with coupling factor adjustment by loop motion.

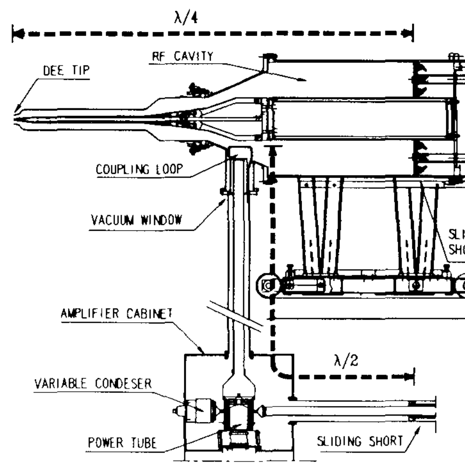


Fig. 1. Schematic cross section of the VINCY Cyclotron RF system with "detuned primary coupling".

The "detuned primary coupling" was used for the VINCY Cyclotron RF system. VINCY is an isochronous cyclotron with four sectors and two RF cavities of λ/4 type [6]. The frequency range is 17-31 MHz, the frequency is varied by a sliding short, the maximal RF voltage is 100 kV and the maximal power dissipation is 25 kW per cavity. To avoid a complex impedance matching system, the resonant coupling was chosen, that is, each amplifier cabinet forms a λ/2 resonator (Fig. 1), inductively coupled to the cavity by a coupling loop.

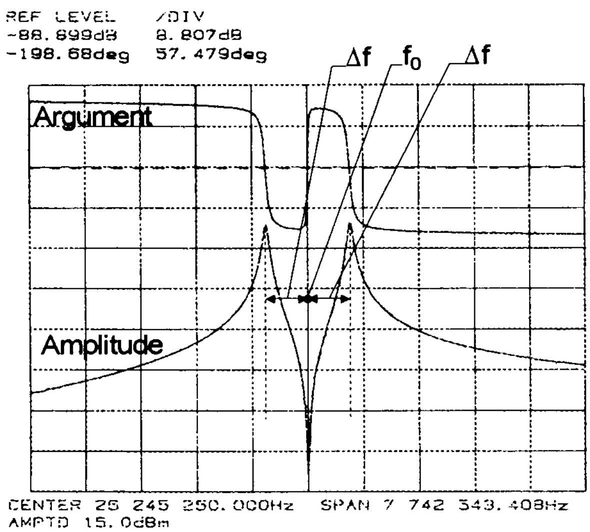


Fig. 2. Frequency response of a resonant coupling RF system (measured at the anode of the power tube) with both resonators tuned to the same frequency.

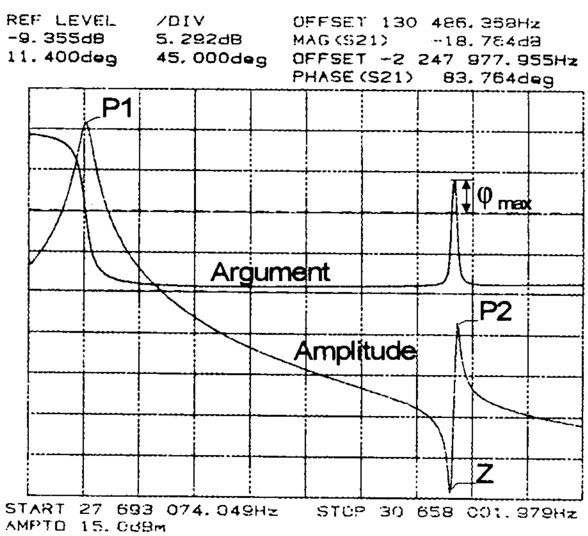


Fig. 3. Frequency response of a system with strongly detuned primary - a working configuration.

## 2 Detuned primary coupling concept

The conventional way of varying the transforming ratio of two coupled resonators is by moving of the coupling loop relative to the direction of the RF magnetic field in the cavity while coupled resonators are tuned the same freqency. The frequency response of the coupled system (measured at the anode of the power tube) has three singularities (whith the zero argumen of the load impedance). The first one (the zero) corresponds to the uncoupled resonators ($f_0$). The other two singularities (poles) occur for the frequencies equal to $f_0 \pm \Delta f$, where $\Delta f$ depends on the coupling factor. Fig. 2 shows the corresponding measurements on the 1:1 models of the resonant cavity and the cabinet.

Since the argument of the load seen by the power tube must be zero, and the impedance at the poles is too high, the only choice for the working point is the zero at the resonant frequency of the uncoupled resonators. This conventional arrangement has two disadvantages: First, in the case of sparking between the dee and the antidee, the secondary is short-circuited, the primary becomes virtually insulated, and the load impedance of the power tube undergoes a large jump (few tens dB). These jumps, in spite of the fast electronic protection of the power tube, shortens its lifetime. The second disadvantage is the need to move the coupling loop for the variation of the dee-to-anode voltage ratio.

In order to avoid these disadvantages, we vary the dee-to-anode voltage ratio $\tau$ (transformer ratio) by detuning the eigenfrequency of the primary relative one of the secondary. This is illustrated in Fig. 3, which gives the corresponding measurement results. When we decrease the primary eigenfrequency, the zero occurs at the frequency close to $f_0$. The left pole (P1) corresponds to the primary, ant the right pole (P2) corresponds to the secondary. While detuning the primary, the signals at the two poles change. The signal at P1 increases, and the signal at P2 decreases. The impedances change the same way. The signal measured on the dee tip does not change significantly. We can choose the working point at P2 since the impedance at this point becomes sufficiently low (few kΩ). Changing the detuning, we can also adjust the transformer ratio $\tau$, which is equal to the ratio of the signals measured at the dee and on the anode of the tube. Therefore, the movement of the loop is not needed; the ideal impedance matching (zero argument at P2) and the desired transformer ratio are attained with only one moving element - the variable capacitor in parallel to the power tube (as in Fig. 1). In this way, we overcome all the technical problems related to the motion of the coupling loop in vacuum.

The distance between the zero and the pole P2 decreases with detuning, and the maximal argument between them $\varphi_{max}$ decreases below 90° (Fig. 3), and can even become negative in case of strong detuning. For a real coupling arrangement, the maximal argument $\varphi_{max}$ should be kept above a certain value (usually 30° - 40°) that ensures the appropriate functioning of the automatic tuning system of the cavity which has a zero argument of the load of the power tube as a reference value. Otherwise (for small $\varphi_{max}$), in case of noise or transients, the automatic tuning system could lock itself on the other zero argument point (the zero at the point Z in Fig. 3), where the impedance is lower for few tens dB. This leads to an emergency stop of the power amplifier caused by the overcurrent protection of the power tube.

For the design of a detuned primary coupling system of a real cyclotron, it is necessary to evaluate the basic coupling parameters: the impedance matching and the transformer ratio $\tau$, with the constraints given by the $\varphi_{max}$ parameter and the maximal space available for the coupling loop. The needs to decrease the loop dimensions and to increase $\varphi_{max}$ are in opposition. For such an evaluation, a suitable calculation approach is needed.

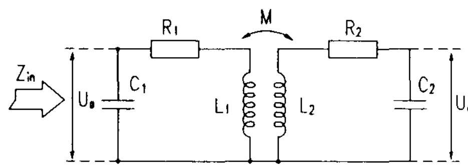


Fig. 4. Lumped circuit approximation of a coupled system.

## 3 Method of calculation

Lumped equivalent circuit models are usually used for the analysis of coupled resonator circuits. Representing a reasonable approximation of real resonators. The quality of the approximation depends mainly on the choice of circuit components. A circuit model that we used is shown on Fig. 4. For a cyclotron cavity, the dee capacitance is the usual value for $C$, and $L$ is determined by the basic resonanace equation, $\omega=(LC)^{-1/2}$. In our case, the choice is determined by the need to calculate the voltage ratio $\tau$ between the dee tip and the anode of the tube, i.e. the voltage ratio on the capacitors $C_1$ and $C_2$,. Our approach is based on the energy balance, i.e. $C$ corresponds to the equivalent impedance $Z_V = 1/\omega C$ which is defined as $Z_V = R_{sh}/Q$. The shunt impedance of a cavity is defined as $R_{sh} = V_0^2/2P$, where $V_0$ is the peak cavity voltage (at the dee tip), and $P$ is the total power loss. With the $Q$ factor defined as $Q = \omega E/P$, ($E$ - energy stored in the cavity), $Z_V$ becomes

$$Z_V = \frac{R_{sh}}{Q} = \frac{V_0^2}{2\omega E} \tag{1}$$

This means that the capacitor $C$ with voltage $V_0$ applied to it would have the same energy content as the resonator. The definition of $Z_V$ is more general than the classical definition of $R_{sh}$ because it can be applied at any point of a resonator:

$$Z_V(x) = \frac{V^2(x)}{2\omega_n E} \tag{2}$$

The voltage at the point $V(x)$ and the energy content of the cavity $E$ can be easily calculated (by a nonuniform line code [7], or a 3D electromagnetic code).

The model of energy transfer between the primary and the secondary with $M$, $L_1$ and $L_2$ is suitable when the energy content of a circuit is equal to $L_n I_n^2$, but not the case of a real resonator. The real energy transfer is dependent on the place where the coupling loop is inserted into the cavity. That is why we must define the $k$ factor more generally as:

$$k = \frac{\omega M}{\sqrt{Z_{I1} Z_{I2}}} \tag{3}$$

where the constants $Z_I$, similar to $Z_V$, are defined as $Z_I = \omega L_{eq}$, $L_{eq}$ being an equivalent inductance having the same energy content as the resonator if the current flow through it is the same as the resonator current at point $x$. $Z_I$ is position dependent, and, analogous to Eq. (4), equal to:

$$Z_I(x) = \frac{2\omega E}{I(x)^2} \tag{4}$$

Applying the Kirchhoff laws to the circuit in Fig. 5, one obtains expressions for the input impedance (the load seen by the power tube) and the the voltage ratio $\tau$ between the dee tip and the anode of the tube depending on impressed frequency $\omega$, resonant frequencies and $Q$ factors of the primary and secondary, constants $Z_{V1}$ and $Z_{V2}$ , and the coupling factor $k$. The $Q$ factors can be calculated [7], or experimentally determined from the resonant curves.

The above expressions were used as a basis of a simple program for numerical evaluation of a detuned primary coupled system. The program's input takes the values of $\omega_1$, $\omega_2$, $Q_1$, $Q_2$, $Z_{V1}$, $Z_{V2}$ and $k$, and evaluates poles and zeros of the $Z_{in}(s)$. For the working frequency corresponding to the pole P2 it solves for $Z_{in}$, $\tau$, and $\varphi_{max}$.

## 4 Measurements on the model

A scale 1:1 model of the VINCY cyclotron cavity was made in order to verify the design parameters. The model has a wooden construction covered with copper sheets with frequency range of 18 to 32 MHz. The amplifier cabinet was coupled to the cavity by a 2 m long line ended with a 100 cm$^2$ coupling loop, according to the Fig. 1. The measurements were done with a Network Analyzer (HP 8751A) and a vector impedance meter (HP 4193A), for several frequencies in the cavity model operating range.

The comparison of measurements and calculations is shown in Fig. 5 and 6. In the measurement on Fig. 5, the frequency of the cavity was kept at 31 MHz, while the amplifier was gradually detuned from 30 to 22 MHz. One can see that the voltage ratio $\tau$ reaches the nominal value for the VINCY cyclotron of 20 dB (100 kV on the dee divided by 10 kV on the power tetrode) for a 5 MHz detuning at 26 MHz. At this point $\varphi_{max}$ has a safe value of 65°. By further detuning the primary, one gets higher voltage ratios $\tau$, but $\varphi_{max}$ gradually decreases, coming close to zero for a detuning of 9 MHz. For the measurements in Fig. 6, the working frequency was varied in the whole range of the model, while for each working frequency the amplifier frequency was detuned to the value for which, according to calculations, the voltage ratio $\tau$ has the nominal value of 20 dB. One can see that for the whole range the argument $\varphi_{max}$ stays above 60°, which enables a safe operation of the automatic tuning system of the cavity. In both figures one can see that the agreement between the measured and calculated results is good.

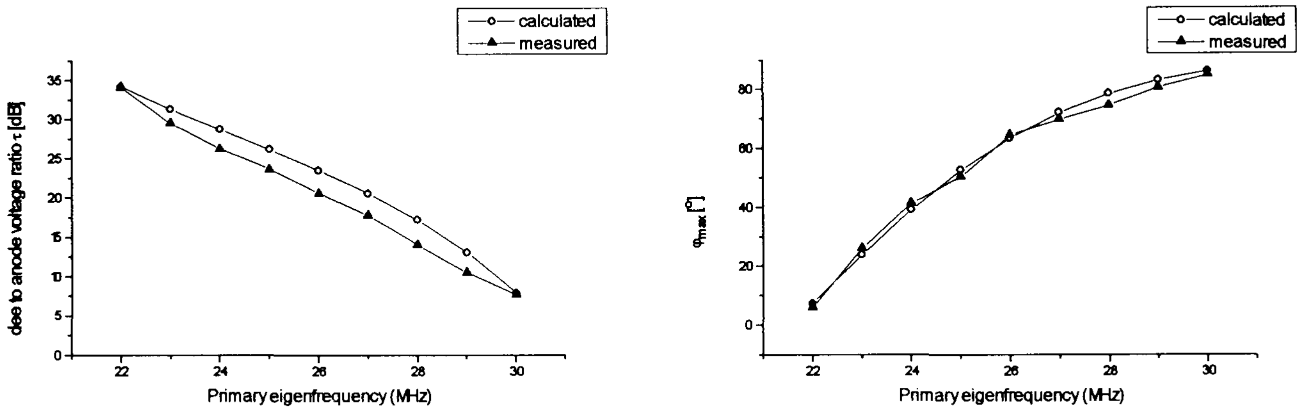


Fig 5. Coupling parameters vs. primary eigenfrequency for secondary frequency of 31 MHz.

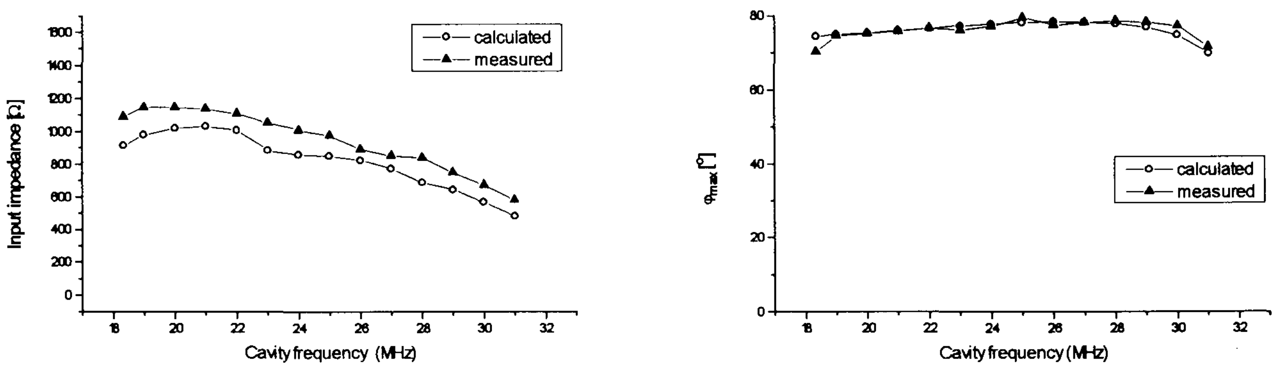


Fig 6. Coupling parameters vs. secondary eigenfrequency for nominal value of the dee-to-anode voltage ratio $\tau$ = 20 dB

## 5 Conclusion

For the cyclotron RF systems with variable frequency operation and inductive coupling, the coupling factor of the coupling loop needs to be changed for different operating frequencies. It was shown that it was possible to achieve the proper impedance matching and dee-to-anode voltage ratio by detuning the primary away from the working frequency, without changing the coupling factor. This allowed the use of a static coupling loop, thus avoiding all the technical problems associated with the movement of the coupling loop in vacuum.

A simple method has been proposed for calculating the main parameters of a system coupled in this way, and used in the design of the VINCY cyclotron RF system. It was verified by measurements on a scale 1:1 model of the VINCY cyclotron RF system and a good agreement between calculations and measurements has proved it to be a useful tool for evaluating the working parameters of a "detuned primary coupling" system.

## References

[1] G. O. Hendry, *IEEE Trans. Nucl. Sci.* NS-12, No. 3 (1965) p. 191
[2] J. Westergaard et al., *Nucl. Instr. and Meth.* A268 (1988) p. 525.
[3] K. L. Erdman, *Proc. 7th Int. Conf. on Cyclotrons and their Applications* (Zurich, 1975) p. 141.
[4] B. Bojović, M. Josipović, and A. Susini, *Proc. 13th Int. Conf. on Cyclotrons and their Applications* (Vancouver, 1992) p. 511.
[5] A. Susini, *Design note TRI-DN-92-K202*, (Vancouver, 1992).
[6] B. Bojović, M. Josipović, and A. Susini, *Proc. 3rd European Particle Accelerator Conference* (EPAC 92) (Berlin, 1992) p. 1310.
[7] C. Pagani, *Proc. CERN Accelerator School CERN* 92-03 (Geneva, 1992) p. 501.