COAXIAL QUARTER WAVELENGTH IMPEDANCE CONVERTER FOR COUPLING CONTROL OF TRIODE CAVITY

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Abstract

In this work we describe the development of a coaxial quarter wavelength impedance transformer. The transformer is used for coupling control of a pre-bunching cavity for a triode type thermionic RF gun in Kyoto University Free Electron Laser (KU-FEL) facility. The application of prototype of impedance transformer could convert the coupling situation of the triode cavity from undercoupled to overcoupled state. The advantage of tested prototype is high power tolerance and out vacuum application. Further development of the prototype should ensure coupling control for beam loading compensation.

INTRODUCTION

The KU-FEL (Kyoto University Free Electron Laser) facility uses an S-band 4.5 cell thermionic RF gun as an electron source [1]. The gun is strongly suffering from back-bombardment effect, which causes decrease of beam energy during the macropulse. A promising cure for the electron back-bombardment problem is an introduction of triode configuration. In the triode structure a small pre-bunching cavity is set prior to the main accelerating body for controlling of injection timing. For the triode configuration the reduction of the back streaming electron energy for more than 80% is expected [2].

We have designed a small coaxial cavity as the pre-buncher of thermal emitted electrons. Figure 1 shows the longitudinal and cross sectional view on the triode cavity for the 4.5 cell triode type thermionic RF gun as designed for KU-FEL facility.

The cavity contains thermionic cathode for electron beam generation. For sake of compactness the cavity is coupled to RF power by longitudinal coaxial waveguide. The cathode was designed for overecoupled conditions. The overcoupling is intended to compensate for power absorption by the electron beam. For higher beam current higher overcoupling condition is required. The pre-bunching cavity was fabricated and cold tests at low and high power conditions were performed. However the fabricated cavity was revealed to be in underecoupled conditions [3].

In order to change the coupling conditions of the triode cavity we have developed an external quarter wavelength coaxial impedance transformer. We have applied a prototype of the impedance transformer with successful conversion of the undercoupled conditions to overcoupled. Further development could allow us selective adjustment of the coupling.

In this work we report about coupling conversion for triode cavity applying λ/4 impedance transformer.

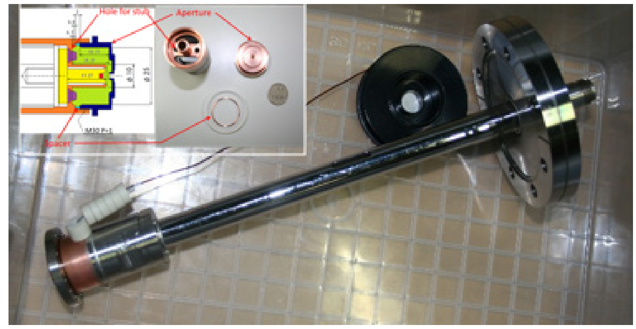

Figure 1: Pre-bunching triode cavity with longitudinal power coupling for a triode type thermionic RF gun.

CAVITY RF COUPLING

Coupler can be defined as a network that allows to transfer power from an RF source to the cavity. Due to impedance and frequency mismatch between the RF power generator and the cavity load some power might be reflected at the coupler. The impedance mismatch is characterized by reflection coefficient Γ. In steady-state case without frequency mismatch the Γ is determined by coupling coefficient κ.

$$\kappa = \frac{1+\alpha|\Gamma|}{1-\alpha|\Gamma|}\begin{cases}\alpha = +1\ overcoupled\\ \alpha = -1\ undercoupled\end{cases}$$

The coupling coefficient represents the ratio of the impedances from the transmission line and the cavity on resonance

$$\kappa = \frac{Z_L}{Z_0}\begin{cases}1 > overcoupling\\ 1 = critical\ coupling\\ 1 < undercoupling\end{cases}$$

In general the reflection coefficient is the ratio of complex amplitudes of inputted and reflected waves. Thus it can be determined from inputted and reflected power ratio at resonance $\Gamma=(P_{ref}/P_{in})^{1/2}$. The corresponded coupling conditions are evaluated from the power transient signal. Figure 2 shows the scheme of transient signals for different coupling conditions.

The triode cavity was evaluated by low power test, which has revealed the undercoupled conditions [3]. For high beam current generation overcoupling conditions are required in order to compensate for beam loading effect. Due to geometrical limitations the coupling change of the cavity is not possible [4]. In order to change the coupling condition we develop an external impedance transformer for the triode cavity.

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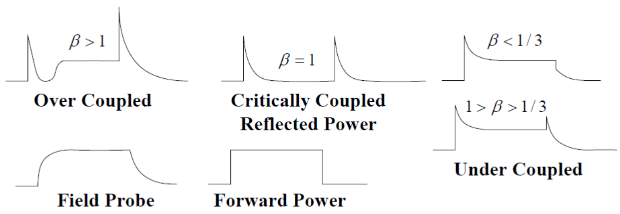

Figure 2: Coupling conditions according to the transient signal of inputted and reflected power [5].

IMPEDANCE TRANSFORMER

The simplest impedance transformer is a waveguide. The impedance of a coaxial waveguide is described by transmission line impedance equation:

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan(\beta l)}{Z_0 + jZ_L \tan(\beta l)}$$

with $\beta=2\pi/\lambda$ and transmission line length *l*. The Z_L is cavity load and Z_0 the characteristic impedance of the transmission line (waveguide).
We are interested in modification of impedances to establish overcoupled conditions ($Z_0 < Z_L$). For this reason we apply a technique of $\lambda/4$ transformer [6]. By insertion of $\lambda/4$ long section with different impedance Z_b the transmission line equation is simplified to

$$Z_{in}\left(l = \frac{\lambda}{4}, Z_0 = Z_b\right) = \frac{Z_b^2}{Z_L}$$

For proper choice of the Z_b the coupling coefficient can be modified. Our system is operated at resonance frequency of f_0=2856 MHz, which correspond to the wavelength of λ=10.5 cm and $\lambda/4$=2.6 cm respectively. The impedance Z_b of the $\lambda/4$ section can be varied by change of the radius of the waveguide.

The $\lambda/4$ impedance transformer has a disadvantage of frequency specification. The load impedance can be transformed efficiently only at a single wavelength.

Impedance Transformer Model

The cavity has longitudinal coupling through a coaxial waveguide (see Fig. 1). The impedance of the waveguide might have an imaginary part $Z_0=R_0+jX_0$. Since this imaginary part jX_0 is unknown we introduce a 2nd section in the $\lambda/4$ impedance transformer. The first section is for impedance transformation and the second section with variable length is for compensation of the imaginary part of coaxial waveguide between the transformer and the triode cavity. The imaginary part disappears when the length of the second section would correspond to $l=\lambda(n+1/4)$, $\lambda(n+1/2)$, $\lambda(n+3/4)$, where n is a natural number. In order to build a prototype of 2-section impedance transformer we need to determine the shortest *l* which would correspond to the $\lambda/4$ position. The 2-section model is illustrated in Fig. 3. According to the Fig. 3 the modified reflection coefficient depends on the impedance ratio of $Z_2(Z_b)$ and Z_0. Which is calculated as follows:

$$\left.\begin{aligned} Z_1\left(l = \lambda\left(n+\frac{1}{4}\right)\right) &= \frac{Z_0^2}{Z_L} \\ Z_2\left(l = \lambda\left(n+\frac{1}{4}\right)\right) &= \frac{Z_b^2}{Z_1} \end{aligned}\right\} \Rightarrow Z_2\left(\frac{\lambda}{4}\right) = \frac{Z_b^2}{Z_0^2} Z_L$$

The coupling coefficient of the undercoupled triode cavity is κ=0.7. By application of the 2- section impedance transformer with Z_b =96.4 Ω the reflection coefficient is Γ=0.4 and modified coupling coefficient is κ=2.3. This result corresponds to overcoupled conditions.

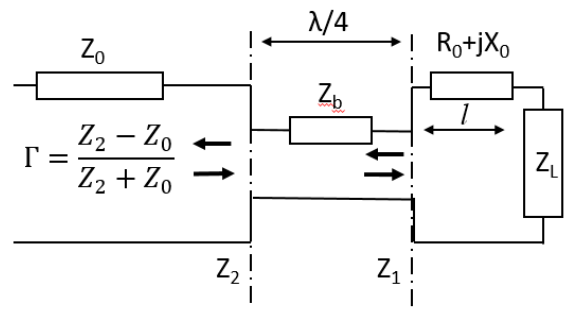

Figure 3: Two-section model of λ /4 impedance transformer.

Prototype

For prototype we have taken an external matched coaxial section (Z_0=50 Ω) and introduced a movable $\lambda/4$ (2.6 cm) long section with specific diameter *a* on the inner conductor of the coaxial waveguide. In order to mitigate arcing and to make the transformer suitable for high input power, the movable section was made with a smaller diameter than the usual inner conductor. Due to geometrical limitations the diameter of the movable section was set to *a*=4 mm which corresponds to the impedance of Z_b=96.4 Ω. Figure 4 shows the photo of the prototype of the impedance transformer.

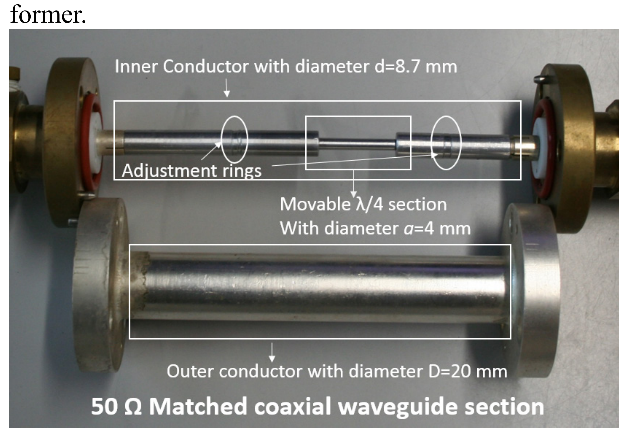

Figure 4: Prototype of the 2-section quarter wavelength impedance transformer.

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The distance l to the cavity load Z_L was found experimentally as a shortest distance at which the cavity resonance is maintained (no influence from imaginary part).

COPLING CONVERSION

Figure 5 shows the transient signals of the cavity with and without impedance transformer. Comparing with the Fig. 2 the signals demonstrate the onversion of coupling conditions from undercoupled to overcoupled state. Thus the transformer is shown to work properly. Evaluation of coupling coefficient from the transient signal gives κ(undercoupled)=0.7 and κ(overcoupled)=2.1. There is a deviation of 10% of calculated and estimated value.

The high power tolerance of the impedance transformer was experimentally checked by feeding high RF power to the system. As the result, we did not detect arcing by input power up to 20 kW. It was demonstrated that the impedance transformer has enough high power tolerance for practical application.

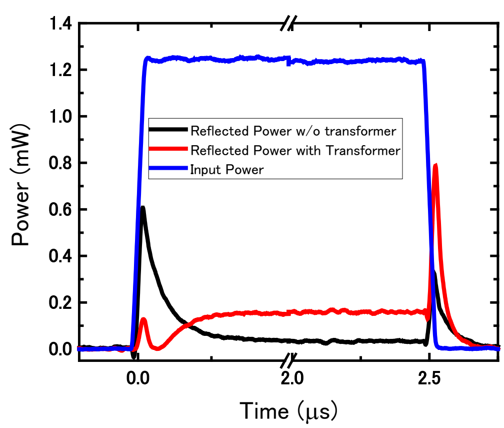

Figure 5: Transient signal of the triode cavity with and without impedance transformer.

Prototype's Uncertainty

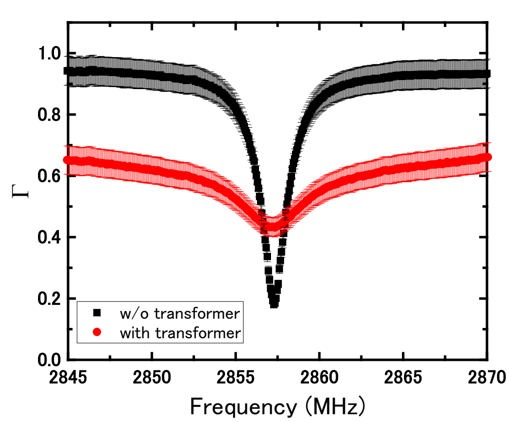

Figure 6: Resonance curve of the triode cavity with and without impedance transformer.

Figure 6 shows the resonance curves of the triode cavity with and without the impedance transformer. The curve with impedance transformer shows power loss of about 40% at off resonance condition. Such power loss is not expected according to calculations shown in the Fig. 7. We suggest that the power loss is caused by low precision of fabrication of the impedance transformer. The impedance transformer used in this experiment is wavelength specific, however the resonance of the cavity may change with environmental conditions. Another point are the rings used for position adjustment (see Fig.4), they might cause additional reflections.

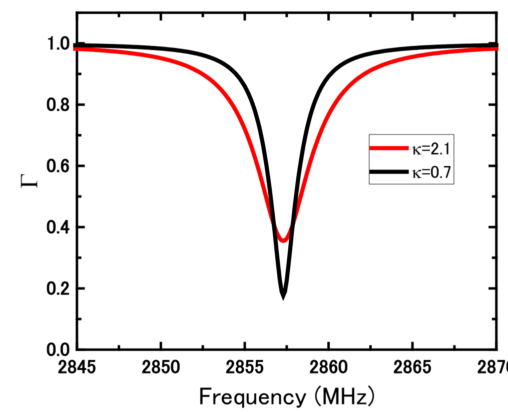

Figure 7: Resonance curve of the triode cavity as calculated for κ(undercoupled)=0.7 and κ(overcoupled)=2.1.

SUMMARY

We have successfully built an external coaxial impedance transformer, which allows us to change coupling from undercoupling to overcoupling condition. The coupling conversion was demonstrated on the triode cavity. The advantage of the proposed transformer design is a tolerance of high input power. Another advantage of the application of impedance transformer is that it could be integrated into the power line as a waveguide without modification of the cavity and breaking the vacuum. However, the prototype we used requires further improvement in order to mitigate power losses.

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