An Operative Measurement of RF Parameters for Slow-Wave Systems

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Abstract

A method for operative measuring the coupling impedance, group velocity and frequency broadband for periodic accelerating structure is described. The method is based on self-excited space harmonic oscillation caused by passing 40-120kV unbunched probe electron beam through the structure. The method has the following features:
- small number of measurements (2-5);
- high enough accuracy at small reflections;
- external RF-source and output beam analyser are not need;
- only one RF-coupler with the structure is used;
- vacuum destruction or reassembling can be avoided.

The method is demonstrated on a travelling-wave linac tapered section inserted into a focusing solenoid.

1. INTRODUCTION

In a number of cases it is necessary to test or measure main characteristics of periodic RF-structure more quickly than it can be done by means of "bold" measurements. One of the ways is using of the special probe beam emerging from the same linac injector or from an auxiliary injector. If this continuous low voltage beam passing through the slow-wave periodic structure is able to cause self-excited RF-oscillation, we can easily estimate impedance, phase and group velocity along the length of effective interaction of the beam and structure.

Stable RF-generation at the same operating frequency was observed in the first section of a multisection RF travelling wave linac when the klystron was turned off. The main conditions of start up and frequency tuning for the effect observed are common with a conventional BWO tube.

2. BASIC RELATIONSHIPS

The method is based on excitation of non-fundamental backward space harmonic at the same operating frequency by the relatively low voltage electron beam and measuring of the threshold current I, corresponding beam voltage Vb, and frequency tuning rate S = dω/dVb. In order to apply the well known relations of the BWO theory [1,2] we have to impose the following conditions:

i) C<<1,
ii) 4qC<<1,
iii) |Γ1Γ2|<<1,
iv) γ-1<<1,
v) τb > 2τf

(1)

where C=(IoRro/4Vb)1/3 is the TWT amplification parameter, qC=(ωb/4πfC)2 is the space charge parameter, ωb is the beam plasma frequency, γ is the beam relativistic factor, Rro is the coupling impedance for the synchronous non-fundamental n-th backward space harmonic, Γ1 and Γ2 are the reflection coefficients with taking into account harmonic transformation for the left and right section edges respectively, τb is the electron beam pulse duration, τf is the filling time for the interaction length.

Under these conditions and using refs. [1,2] we can obtain simple expressions for the space harmonic phase velocity cβ ph, coupling impedance Rro, and group velocity cβ gr:

\[ c_{\beta_{\text{ph}}}(n) = \beta_{\text{ph}} \theta / (\pi - \theta - \pi n), \]
\[ c_{\beta_{\text{b}}}(n) = V_b / \left(8.2N^3I_{\text{s}}\right), \]
\[ R_{ro} = \frac{V_b (1+\xi /\xi)}{\epsilon m_c^2 \gamma^2 \beta_b^2 S}, \]

(2)

where λ=2πc/f, N=L/λ, βph is the number of slow waves per interaction length L, βph and θ are the normalised phase velocity and operating mode for the fundamental accelerating harmonic (n=0). The first line in (2) can be obtained from Brillouin diagram plotted for a periodically loaded structure.

We have assumed in deriving (2) that the measurements are made when the oscillation corresponds to the lowest (zero) BWO band when fphn - fph is minimum and oscillation power is maximum for this band.

For a conventional disk loaded waveguide (DLWG) with βph=1, θ=π/2, L = 1m and for n= -1 we can easily estimate from (2), that Vb ≈ 35kV and I, is of the order of hundred milliampers. If we deal with crossed bar jungle gum structure we can have the threshold current of the order of tens-hundred amperes.

If the reflections are strong, expressions (2) are no longer valid. However, in case τb >> τf the coupling impedance Rro can be defined by the following way (see ref. [2]):

\[ R_{ro} = V_b \left(1-\left|\Gamma_1\Gamma_2\right|\right) / (8.2N^3I_{\text{s}}) \]  

(3)

To determine the frequency broadband we should to find the points of oscillation breakdown on the plot of frequency versus beam voltage.

3. EXPERIMENT

3.1. Experimental set-up
The experimental layout is shown in Figure 1. The injector with thermionic gun can deliver the electron beam with the following maximum parameters of current, voltage and pulse duration: I_0 = 7 A, V_b = 120 kV, t_b = 7 μs. The structure consists of tapered sectioned DLWG with internal RF ohmic load and symmetrized RF-coupler. Focusing is provided by a set of three solenoid coils with variable field profile. Magnetic field maximum is about 0.13 T. Another elements are intended for measuring the amplitude, frequency and time parameters of generated signal and for tuning the phase and absolute value of the reflection coefficient |Γ_1| seen by the section in the regime of self-excited oscillation.

The main parameters are plotted along the section in Figure 2. The relative amplitude parameter
\[ E_{\text{rel}} = \sqrt{\frac{R_{\text{sh}}}{Q_{\text{p}}}} \]
and wave phase velocity \( v_p \) are presented in the Figure 2 for both fundamental harmonic \( n = 0 \) and backward space harmonic \( n = -1 \). Here \( P \) is the power of the travelling wave, \( Q \) is the waveguide quality factor, \( E_n \) is the electric field amplitude and \( R_m \) is the shunt impedance for the \( n \)-th space harmonic.

The section consists of three main parts: \( L_1 \) is the prebunching subsection at \( \beta_n = \text{const} \approx \beta_b = v_b / c \) (π/2 accelerating mode); \( L_2 \) is the bunching and accelerating subsection at \( \beta_{\text{ph}} = \text{var} \) (π/2 mode) and supplied by phase shifting cells; \( L_3 \) is the accelerating subsection with \( \beta_{\text{ph}} = 1 \) (2π/3 accelerating mode), which is separated from \( L_2 \) by matching cell and supplied by the end cells covered by an absorbing layer. The last \( L_3 \) subsection has the following geometry: loading parameter a/λ = 0.11, disk thickness b/λ = 0.0365, internal radii ratio a/b = 0.26.

3.2 Experimental results and some features of BWO-TWT oscillation in tapered accelerator-buncher section

Figure 3 shows the plots of measured peak power \( P_\text{m} \) and generated pulse length \( t_g \) versus the beam current at beam voltage \( V_b = 100 \text{kV}, t_b \approx 5.5 \mu s \). The measured width of the dominant frequency component is about 1 MHz and the optimum value of reflection coefficient \( |Γ_1| \) is about 0.17.

Figure 2. The parameters of the experimental section Relative amplitude (curve 1), dimensionless phase velocity for the fundamental and backward -1 space harmonic (2,3) and group velocity (4) are plotted along the section.

Pulse length increasing took place while the leading edge of the RF-envelope was moving to the left. We observed also that the trailing edge of the generated pulse arrives before that of the beam current pulse. The maximum electronic efficiency of the oscillation was calculated as a ratio of energies and has reached the value of 65% with taking into attention the reduction of the RF pulse length compared with e.b. pulse length. This compression effect is due to the action of the second feedback loop due to reflection from the RF coupler. Efficiency depends very
strong on the quality of the adjustment of the following parameters:
- the voltage standing wave ratio of the section (VSWR "cold" measurements) is close to 1.25 ($f = 1817 \pm 0.2$ MHz) due to mismatching of absorbing load ($|\Gamma_2| < 0.11$);
- phase and absolute value of the coefficient of reflections from the external load;
- focusing solenoidal field profile along the section.

The frequency sensitivity is plotted in Figure 4 for the beam currents in the range of 0.25-0.6 A. Under some conditions (focusing field profile and $\Gamma_1$ readjustment) we have observed ripples in RF-envelope with period $\approx 0.7 \mu s$ (that is about twice of the filling time $t_f$ for the section) and relative amplitude variation up to 30% at $I_b = 6 \mu s$ and $t_b = 5.1 \mu s$. As the beam current was increasing $I_b > 2.5 A$ the ripples were converting into chaotic pulsations.

3. THE ANALYSIS OF THE EXPERIMENTAL RESULTS

Since the injected beam with $\beta_0 = 0.5-0.6$ is close to the synchronism with $-1$ space harmonic in the L3 subsection we should replace value $L$ in (2) by $L_0$ with the exception of cells with high RF-losses. Expressions (2) are valid because $C = 0.05 << 1$ and $|\Gamma_1, \Gamma_2| = 0.019 << 1$. The experimental value of the threshold current $I_0$ is 0.25 A at $V_b = 96$ kV.

Calculated according to (3) coupling impedance is 120 Ohms. On the other hand, the coupling impedance for $-1$ space harmonic calculated with the help of handbook [3] is equal to $R_c = 123$ Ohms with taking into account of rounding on internal selvages of disks.

Calculated $\beta_0$ local value is -0.011 at $V_b = 88$ kV and $S=170$ Hz/V, while for the averaged over broadband value $<S> = 72$ Hz/V $\beta_0 = -0.0047$. Note, the precise value of $|\beta_0|$ is 0.011 at $f = 1818.5$ MHz. We suppose the nonlinearity of Figure 4 plot is due to reflected waves neglected in (2).

Oscillation breakdown takes place at $V_b < 64$ kV and $V_b = 101$ kV that corresponds to cut-off frequencies 1816.5 and 1819 MHz respectively. It means that the experimental frequency broadband is equal to 2.5 MHz whereas from cold measurements with help of RF line we obtained frequency broadband 2.2 MHz. Note, that this broadband corresponds to entire tapered structure having subsections, phase shifting cells, RF-transformer and internal load while the broadband defined from dispersive curve for the L3 subsection is equal to 24 MHz.

The enormously high efficiency of RF generation with respect to a conventional DWO and other features were analysed numerically [4]. In the first two subsections we have basically klystron type of bunching, the second subsection plays a role of a drift space. Beam prebunching takes place in the first subsection and results in improved efficiency.

4. SUMMARY

1. The advantages of the method considered are simplicity at minimal interference into section construction and applicability to structures having subsections with constant geometry. In the last case the oscillation can acquire some features known for TWT-BWO cascade oscillator and twistron oscillator supplied by a delayed feedback loop when the reflected wave causes the initial beam prebunching in the first subsection.

2. The method requires using of external source of intense e.b., external focusing system and recalculation of the impedance for the fundamental mode that can be regarded as the main disadvantages.

3. In spite of the features mentioned above the method has potential feasibility for operative measurement or testing of a large number of identical RF sections.

5. REFERENCES


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