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 "cold" 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 as for fundamental wave by the relatively low voltage electron beam and measuring of the threshold current I_s, correspondent beam voltage V_b and frequency tuning rate $S = \Delta f / \Delta V_b$. In order to apply the well known relations of the BWO theory [1,2] we have to impose the following conditions:

i) $C \ll 1$,
ii) $4qC < 1$,
iii) $|\Gamma_1 \Gamma_2| \ll 1$,   (1)
iv) $\gamma - 1 \ll 1$,
v) $t_b > 2t_f$,

where $C = (I_b R_{cn}/4V_b)^{1/3}$ is the TWT amplification parameter, $qC = (\omega_b/4\pi fC)^2$ is the space charge parameter, ω_b is the beam plasma frequency, γ is the beam relativistic factor, R_{cn} is the coupling impedance for the synchronous non-fundamental n-th backward space harmonic, Γ_1 and Γ_2 are the reflection coefficients with taking into account harmonic transformation for the left and right section edges respectively, t_b is the electron beam pulse duration, t_f 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 $c\beta_{phn}$, coupling impedance R_{cn} and group velocity $c\beta_{gr}$:

$$\begin{cases} \beta_{phn} = \beta_{ph0}\theta/(\pi - \theta - \pi n), \\ \beta_b = 1/\left(\beta_{phn}^{-1} - \lambda/L(QC)^{3/4}\right), \\ R_{cn} = V_b/\left(8.2N^3 I_s\right), \\ \beta_{gr} = \beta_b/\left(1 - \dfrac{e}{m_0 c^2 \gamma^3 \beta_b} \cdot \dfrac{f}{S}\right), \end{cases} \quad (2)$$

where $\lambda = 2\pi c/f$, $N = L/\lambda\beta_{phn}$ is the number of slow waves per interaction length L, β_{ph0} 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 $\beta_{phn} - \beta_b$ is minimum and oscillation power is maximum for this band.

For a conventional disk loaded waveguide (DLWG) with $\beta_{ph0}=1$, $\theta=\pi/2$, L $\approx$ 1m and for n= -1 we can easily estimate from (2), that $V_b \approx 35$kV and I_s 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 $t_b \gg t_f$ the coupling impedance R_{cn} can be defined by the following way (see ref. [2]):

$$R_{cn} = V_b\left(1 - |\Gamma_1\Gamma_2|\right)/(8.2N^3 I_s) \quad (3)$$

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_b = 7A, V_b = 120kV, t_b = 7μs. 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 0.13T. 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.
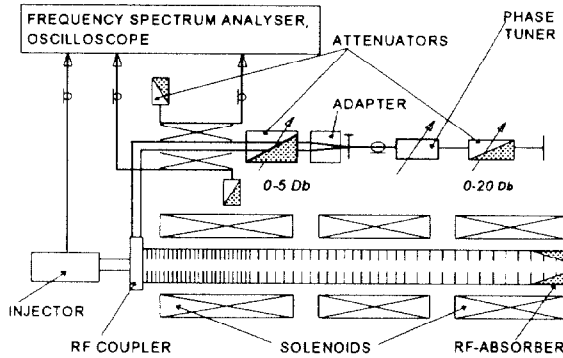

Figure. 1. Experimental layout for measurement of the parameters of the self-excited oscillation in DLWG tapered section.

The main parameters are plotted along the section in Figure 2. The relative amplitude parameter

$$E_n\lambda/\sqrt{P}=\sqrt{R_{sn}2\pi\lambda / (Q\beta_{gr})}$$ and wave phase velocity

β_{phn} 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_{sn} is the shunt impedance for the n-th space harmonic.

The section consists of three main parts: L_1 is the prebunching subsection at β_n = const ≈ β_b = v_b /c (π/2 accelerating mode); L_2 is the bunching and accelerating subsection at β_{pho} = var (π/2 mode) and supplied by phase shifting cells; L_3 is the accelerating subsection with β_{pho}=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 t/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_g and generated pulse length t_g versus the beam current at beam voltage V_b ≈ 100kV, t_b ≈ 5.5μs. The measured width of the dominant frequency component is about 1MHz and

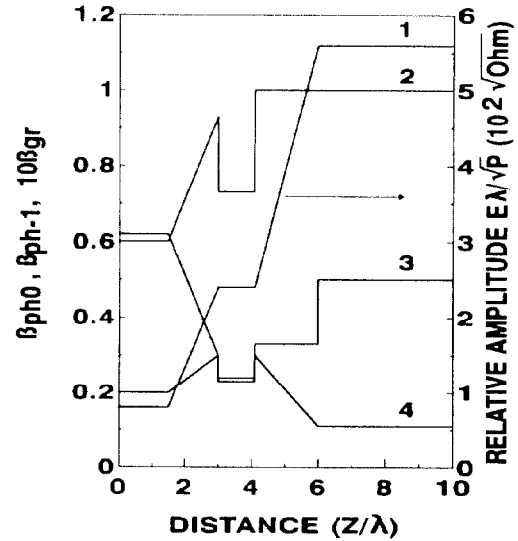the optimum value of reflection coefficient $|\Gamma_1|$ is about 0.17.

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.
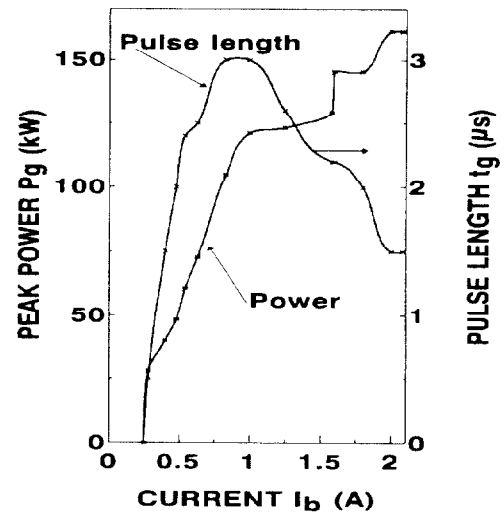

Figure 3. Generated peak power and RF pulse length as a function of the beam current.

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±0.2 MHz) due to mismatching of absorbing load ($|\Gamma_2| \approx 0.11$);
- 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 0.25-0.6A . Under some conditions (focusing field profile and Γ_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 $t_b = 6$ μs and $t_g = 5.1\mu s$. As the beam current was increasing $I_b > 2.5A$ the ripples were converting into chaotic pulsations.

3. THE ANALYSIS OF THE EXPERIMENTAL RESULTS

Since the injected beam with β_b =0.5-0.6 is close to the synchronism with -1 space harmonic in the L_3 subsection we should replace value L in (2) by L_3 with the exception of cells with high RF-losses. Expressions (2) are valid because $C \approx 0.05 << 1$ and $|\Gamma_1 \Gamma_2| \approx 0.019 << 1$. The experimental value of the threshold current I_s is 0.25A at $V_b = 96kV$.
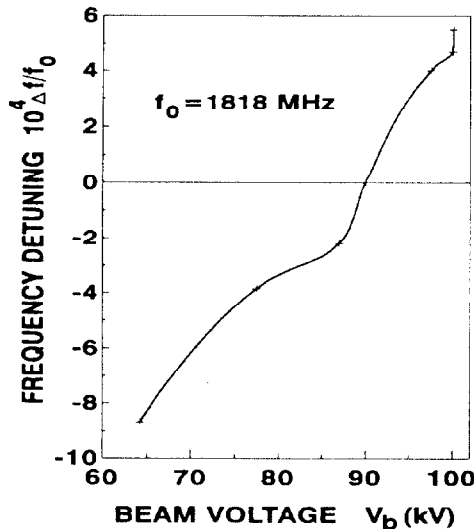

Figure 4. The frequency sensitivity plot for the generated RF-pulse.

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 β_{gr} 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 $\beta_{gr} = -0.0047$. Note, the precise value of $|\beta_{gr}|$ 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 $V_b < 64kV$ and $V_b > 101kV$ that corresponds to cut-off frequencies 1816.5 and 1819MHz respectively. It means that the experimental frequency broadband is equal to 2.5MHz whereas from cold measurements with help of RF line we obtained frequency broadband 2.2MHz. 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 L_3 subsection is equal to 24MHz.

The enormously high efficiency of RF generation with respect to a conventional BWO 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 twystron 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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