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APPLICATION OF HIGH FREQUENCY SYSTEM FOR IMPROVEMENT OF OUTPUT PROPERTIES OF STANDING WAVE ELECTRON LINEAR ACCELERATORS

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ABSTRACT

This article discusses high-frequency systems of standing wave linear electron accelerator which enable fine tuning of high-frequency energy supplied to accelerating resonator sections upon simultaneous variation of time constant of transient process of electric fields setup in sections. In these systems complete decoupling of generator from high-Q accelerating sections is achieved, the influence of current load by accelerating sections decreases, and beam output properties are improved.

Keywords: accelerator power supply, magnetron, Waveguide Bridge, phase inverter, attenuator, dissipative load, transient process.

1. INTRODUCTION

Standing wave electron linear accelerators (linac) in some cases are more compact and efficient in comparison with running wave linac (Filatov & Shilov, 1984). As a rule, accelerating system of such facilities is comprised of contoured cavity resonators of biperiodic slow wave structures (BSS) of various types (Novozhilov, *et al*. 2016). High frequency (HF) power of accelerating sections in such linacs is supplied by magnetron or klystron amplifier and generator decoupling from high-Q accelerating resonators are performed by ferrite valves, circulators or HF bridges (Novozhilov, *et al.* 2014).

Power supply of linac accelerating sections from magnetron via Waveguide Bridge in terms of efficiency, dimensions and maintainability, cost of main and auxiliary equipment, is preferred in comparison with other power supply types (Vikulov, *et al*. June 1979). In addition, with appropriate selection of bridge properties it is possible to stabilize magnetron frequency more than by an order of magnitude. Figure-1 illustrates flow chart of such linac (Vikulov, *et al*. 1979).

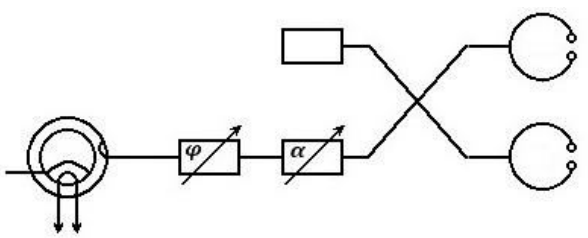

Figure-1. HF system of linac with power supply via Waveguide Bridge.

In such accelerator two equal accelerating sections are connected to output arms of HF Bridge which supplies generator from high-Q load. HF energy, reflected from the section upon transient process of electromagnetic field setup, is supplied to waveguide dissipative load. HF energy level supplied to bridge input is tuned by attenuator, which enables variation of electron energy at linac output.

Nowadays numerous attenuator designs are known, operating at high energy level (Helszajn, 1978). In (Vikulov, *et al*. 1979) attenuator of adsorption type is used, which is characterized by small dimensions, simplicity and maintainability. Such attenuator is a fragment of rectangular waveguide, its narrow wall is connected to two low-Q tunable prismatic alsifer coated resonators at the distance of $\frac{3}{4}\Lambda$, where Λ is the wave length in the waveguide.

The resonators are coupled with waveguide via holes in waveguide narrow wall and retuned by means of short-circuit choke plungers. Such attenuator enables fourfold tuning of passing HF energy at relatively low reflections at it in overall tuning range. However, the considered attenuator adsorbs some energy even at strong detuning of its resonators, besides, it is impossible in principle to achieve it complete matching with carrier line link in total range of energy tuning.

This work discusses HF system of standing wave linac, permitting fine tuning of HF energy level supplied to accelerating sections and providing complete generator decoupling fro, high-Q load, which improves significantly output beam properties.

2. EXPERIMENTAL

HF system with fine tuning of energy supplied to accelerating sections

Flow chart of such HF system is illustrated in Figure-2. Her HF energy from generator is supplied to the input of waveguide coupler at the coupling ratio α. One output arm of the coupler is terminated with dissipating load, and the second output arm is connected with input of HF Bridge. Reflected HF energy is supplied to the second input arm of the coupler. The considered flow chart can be suitably analyzed using scattering matrix of the elements included in the flow chart.

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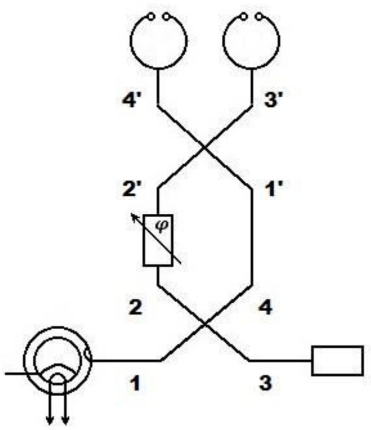

Figure-2. HF system of linac with power supply via directional coupler and Waveguide Bridge.

Let us consider that the reflection coefficients of accelerating sections are the same and equal to $\dot{\Gamma}$, and the reflection coefficient of load is zero. Scattering matrices of directed coupler and HF bridge (arm numeration corresponds to Figure-2) are as follows (Novozhilov, *et al.* 2016).

$$[S]=\begin{bmatrix} 0 & 0 & \alpha & i\beta \\ 0 & 0 & i\beta & \alpha \\ \alpha & i\beta & 0 & 0 \\ i\beta & \alpha & 0 & 0 \end{bmatrix},\ [S']=\frac{1}{\sqrt{2}}\begin{bmatrix} 0 & 0 & 1 & i \\ 0 & 0 & i & 1 \\ 1 & i & 0 & 0 \\ i & 1 & 0 & 0 \end{bmatrix},\ \alpha^2+\beta^2=1. \quad (1)$$

Equations for normalized amplitudes of falling and reflected waves in the arms of coupler and bridge can be written as:

$$a_1=a_g, a_2=-\frac{a_g\beta\dot{\Gamma}e^{-i\varphi}}{1-i\alpha\dot{\Gamma}e^{-i\varphi}}, a_3=a_4=0;$$

$$b_1=b_2=0, b_3=a_g\frac{\alpha-i\dot{\Gamma}e^{-i\varphi}}{1-i\alpha\dot{\Gamma}e^{-i\varphi}}, b_4=a_g\frac{i\beta}{1-i\alpha\dot{\Gamma}e^{-i\varphi}}; \quad (2)$$

$$a_1'=a_g\frac{i\beta}{1-i\alpha\dot{\Gamma}e^{-i\varphi}},\ a_2'=0,\ a_3'=\frac{a_g}{\sqrt{2}}\frac{i\beta\dot{\Gamma}}{1-i\alpha\dot{\Gamma}e^{-i\varphi}}, a_4'=ia_3';$$

$$b_1'=0, b_2'=-\frac{a_g\beta\dot{\Gamma}}{1-i\alpha\dot{\Gamma}e^{-i\varphi}}, b_3'=\frac{a_g}{\sqrt{2}}\frac{i\beta}{1-i\alpha\dot{\Gamma}e^{-i\varphi}}, b_4'=ib_3'.$$

where a_g is the normalized amplitude of generator voltage wave; a_i, a_i' are the normalized amplitudes of falling waves in coupler and bridge (i is the arm number); b_i, b_i' are the normalized amplitude of reflected waves; φ is the cumulative phase progression upon the wave passage from arm 4 to arm 2 of the coupler.

As mentioned in (Ginzton, 1957), the reflection coefficient of accelerating waves equals to:

$$\dot{\Gamma}=-\frac{1-f_0^2/f^2+if_{0(\beta_0-1)}/fQ_0}{1-f_0^2/f^2+if_{0(\beta_0+1)}/fQ_0}, \quad (3)$$

where f is the generator frequency, f_0 is the resonant frequency of sections, Q_0 is the basic Q-factor of sections, β_0 is the coupling coefficient of section with input waveguide.

It follows from Equations (2) and (3) that at $f=f_0$ and $|\dot{\Gamma}|=\alpha$, using phase inverter, it is possible to select such mode upon which the energy supplied to load is zero and all HF energy from the generator is dissipated in accelerating sections. It can be readily demonstrated that upon variation of φ the active power from accelerating sections P will vary in the range of:

$$(\tfrac{1-\alpha^2}{1+\alpha^2})^2P_g\le P\le P_g,$$

where $P_g=\frac{1}{2}|a_g|^2$ is the generator power.

Such operation mode of linac HF system can be implemented at two values of coupling coefficient:

$$\beta_0=1+\alpha/1-\alpha \quad (4)$$

or

$$\beta_0=1-\alpha/1+\alpha. \quad (5)$$

In the first case (4) the accelerating sections are overcoupled and in the second case (5) they are undercoupled.

Now let us consider the aspect of HF field setup in the sections upon transient process and write the equation for normalized wave amplitude in load:

$$b_n=b_3=\frac{\alpha\left(1-f_0^2/f^2-if_{0(\beta_0+1)}/fQ_0\right)+i\left(1-f_0^2/f^2-if_{0(\beta_0-1)}/fQ_0\right)e^{-i\varphi}}{\left(1-f_0^2/f^2-if_{0(\beta_0+1)}/fQ_0\right)+i\alpha\left(1-f_0^2/f^2-if_{0(\beta_0+1)}/fQ_0\right)e^{-i\varphi}}a_g.$$

In the case of overcoupled sections and when under stable conditions at $f=f_0$ there is not energy in load, that is, at $ie^{-i\varphi}=1$, the latter equation is as follows:

$$b_n=\frac{\left(1-f_0^2/f^2-if_{0(\beta_{0\,eq}-1)}/fQ_0\right)}{\left(1-f_0^2/f^2-if_{0(\beta_{0\,eq}+1)}/fQ_0\right)}a_g, \quad (6)$$

where $\beta_{0\,eq}=\beta_0\,1-\alpha/1+\alpha=1$.

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Equation (6) coincides exactly with the equation for b_n in Figure-1, if $\beta_0 = 1$, that is, the transient process runs with the time constant:

$$\tau_0 = {}^{Q_0}/_{2\pi f_0}.$$

When maximum energy is supplied to load,

$$\beta_{0\,eq} = \beta_0 \; {}^{1+\alpha}/_{1-\alpha} = \left({}^{1+\alpha}/_{1-\alpha}\right)^2,$$

the transient process runs with the time constant:

$$\tau = \tau_0 \, {}^{2}/_{(\beta_{0\,eq}+1)}.$$

Thus, it is possible to conclude that in the case of overcoupled accelerating sections simultaneously with decrease in supplied energy the transient process of HF field setup is accelerated. In the case of undercoupled sections, when supplied energy decreases, the duration of HF field setup increases.

Therefore, if the coefficients of coupling of accelerating resonators with carrier line link satisfy Eq. (4), then this flow chart facilitates tuning of energy supplied to accelerating resonators upon simultaneous variation of time constant of the transient process. Amount of control is determined by the coupling ratio of directional coupler α. Herewith, the generator operates for tuned load in overall tuning range of phase inverter. However, there are operation modes when on individual fragments of carrier line link there occurs overvoltage in comparison with input of directional coupler.

Let us consider an individual case when $\alpha = {}^{1}/_{\sqrt{2}}$, that is, when two HF bridges are used in the flow chart. Then the active power of the accelerating sections can be written as $P = \frac{1}{5+4\cos\varphi} P_g$, hence, ninefold tuning of active power is achieved, and the time constant of the transient process decreases by 18.5 times. Figure-3 illustrates active power of accelerating sections as a function of cumulative wave phase progression φ between the bridge arms.

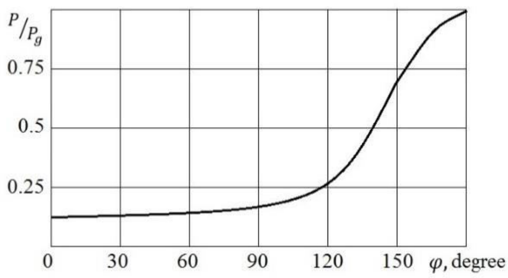

Figure-3. Relative active power of accelerating structure as a function of wave phase progression upon its passage from arm 4 to arm 2 of directional coupler.

The illustrated results are obtained on assumption of no current load on accelerating sections. With current load the conditions for $\dot{\Gamma}$ are the same, but in this case $\dot{\Gamma}$ is the function of β_0 and beam parameters. In particular, for ultrarelativistic point bunches in maximum accelerating field, and at $f = f_0$ the equation for $\dot{\Gamma}$ is written as in (Filatov & Shilov, 1985):

$$\dot{\Gamma} = \frac{\beta_0 - 1}{\beta_0 + 1} - \frac{I\sqrt{\beta_0}}{\beta_0 + 1}\sqrt{\frac{R_{eff}L}{P_0}}, \qquad (7)$$

where I is the pulse current, R_{eff} is the effective shunt resistance of accelerating sections, L is the section length, P_0 is the active energy at section input.

On the basis of Eq. (7) and accounting for $|\dot{\Gamma}| = \alpha$ the following equations for β_0 can be readily obtained:

$$\beta_0 = \left(\frac{\hat{I}}{2(1-\alpha)} + \sqrt{\frac{I^2}{4(1-\alpha)^2} + \frac{1+\alpha}{1-\alpha}}\right)^2, \qquad (8)$$

$$\beta_0 = \left(\frac{\hat{I}}{2(1+\alpha)} + \sqrt{\frac{I^2}{4(1+\alpha)^2} + \frac{1-\alpha}{1+\alpha}}\right)^2, \qquad (9)$$

where $\hat{I} = {}^{I}/_{\sqrt{P_0 R_{eff} L}}$ is the reduced current.

Let us note that Eqs. (5) and (6) are particular cases of Eqs. (8) and (9) at $I = 0$. Finally it should be mentioned that in the considered HF system of linac the influence of current of beam of accelerated particles on output energy decreases with increase in α.

2.1 Improvement of output properties of standing wave electron linear accelerators

Output properties of standing wave electron accelerators operating in pulse mode are significantly influenced by transient process of accelerating fields setup in high-Q resonant sections. Its duration at characteristic duration of HF pulse of 3 μs achieves approximately 1 μs. Due to the transient process electron beam does not gain energy in initial stage of HF pulse and, besides, there occurs spread in average energies of particle bunches.

This can be avoided by delay in electron injection pulse. It was demonstrated in (Vikulov, *et al.* 1982) that addition of delay in electron injection pulse with regard to HF pulse improves significantly output properties of standing wave linac. However, efficiency of the facility decreases as a consequence of increase in wastes of HF energy upon transient process. High losses of HF energy due to transient process occur even in facilities without injection pulse delay with regard to HF pulse.

Let us clarify this statement. It is known that the resonator active power varies as follows:

$$P(t) = P_0\left[1 - exp\left(-\frac{\omega_0}{Q_l}\right)\right], \qquad (10)$$

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where P_0 is the established value of the resonator active power, $Q_l = \frac{Q_0}{1+\beta}$ is the loaded Q-factor of the resonator, Q_0 is the basic Q-factor of the resonator, β is the coupling coefficient of resonator with supplying line, t is the time, $\omega_0 = 2\pi f_0$, f_0 is the resonator eigenfrequency.

According to Eq. (10), power losses upon transient process are determined as follows:

$$W_{el} = \frac{P_0 Q_0}{(1+\beta)\omega_0}.$$

The losses are especially high in the systems with high Q-factors and can constitute significant portion at low durations of HF pulse. For the considered class of accelerators the pulse duration is in comparatively narrow range of about $1.5 \div 5\ \mu s$, which is determined on the one hand by time of oscillation setup in self-excited generator (magnetron), and on the other hand by arcing, cathode emission fall and transition of generation frequency to another oscillation type (Lebedev 1972). Therefore, energy losses due to transient process in standing wave linac can equal to tens of percent.

Figure-4 illustrates flow chart of cascade connection of HF Bridge, facilitating improvement of output propertied of multisection linacs with simultaneous increase in their efficiency. This was achieved by connection of output arms of the first bridge to two grouping sections. The second input arm of the latter bridge includes dissipative load. Herewith, the following conditions are valid:

$$\beta_0 = \frac{2P_g - P_{01} + 2\sqrt{P_g^2 - P_g P_{01}}}{P_{01}}, \qquad (11)$$

$$\beta_k = 2(N-k) - 1 + 2\sqrt{(N-k)(N-k-1)}, \qquad (12)$$

where β_0 is the coupling coefficient of grouping sections with the arms of the first bridge, P_g is the rated active power of HF generator, P_{01} is the rated active power of grouping sections, β_k is the coupling coefficient of each pair of accelerating sections with the arms of connected bridge, N is the total number of HF bridges, $k - 1, 2, \ldots, N-1$ is the number of pair of accelerating sections connected to one bridge.

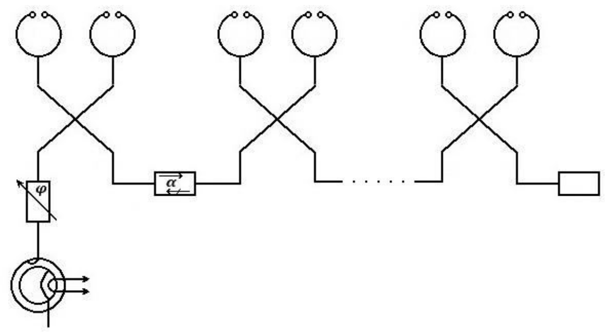

Figure-4. HF power system of multi-section linac.

Generally buncher consumes minor portion of supplied energy from HF generator, hence, in the considered case the main portion of falling wave is reflected from it. According to Eq. (11), the value of the coupling coefficient with supplying waveguide corresponds to the mode of strong overcoupling. Hence, the duration of transient process is significantly reduced, the time constant of the process is $\tau = \frac{Q_0}{(1+\beta)\omega_0}$, где$\beta_0 \gg 1$.

In subsequent sections the transient process is accelerated both due to increase in β_k, and due to increase in HF energy supplied to section input in comparison with steady mode as a consequence of reflections from previous sections. Therefore, even in the last pair of accelerating sections operating in the mode of critical coupling the transient process is accelerated to some extent.

3. RESULTS AND DISCUSSIONS

If HF system is arranged according to the considered flow chart, then the transient process in buncher will be faster by an order of magnitude. This will improve the conditions of electron acceleration at the leading edge of HF pulse envelope and permit to eliminate nearly completely particles, which previously were accelerated at trailing edge of pulse. As a consequence, the width of energy spectrum at accelerator output will decrease by 2-3 times. Herewith, the losses of HF energy in waveguide load will decrease by 30%, that is, accelerating current slightly increases (by about 5%). It should be mentioned, that HF system becomes more compacted due to elimination of one dissipative load from this flowchart.

Figure-5 illustrates modified HF system for three-section accelerator with the following coupling coefficient of resonator sections with supplying waveguides:

$$\beta_1 = \beta_2 = 3 + \sqrt{2}, \beta_3 = 1,$$

that is, the first two consume 25% of HF generator energy each, and the third one consumes 50%. At such arrangement well bunched electrons with low phase extent are obtained at the output of the second section. Using phase inverter and varying entry phase of bunches into the third section, it is possible to perform readily fine tuning of electron energy at the accelerator output. Coupling ratio of HF coupler slightly differs from 3 dB, thus facilitating achievement of stabilization of magnetron frequency by high-Q resonators, herewith, the third section actually does not influence on operation of HF generator, since it is completely decoupled by ferrite isolator.

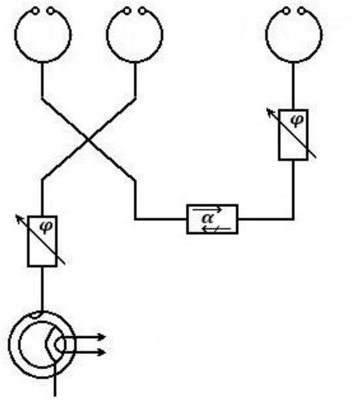

Figure-5. HF power system of three-section linac.

Figure-6 illustrates HF system facilitating improvements of spectral properties of two-section accelerator. This is achieved by replacement of waveguide load with HF energy absorber made in the form of short section of circular iris waveguide (CIW), or another decelerating system containing internal waveguide dissipating load at the output.

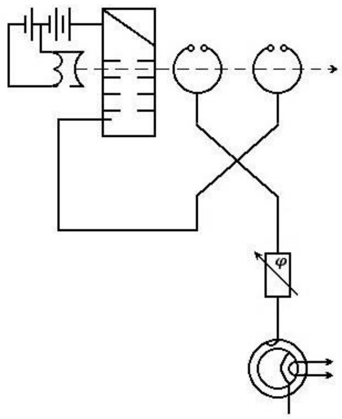

Figure-6. HF power system of two-section linac with CIW short section as deflecting element.

The section is located between injector and the first accelerating cell in perpendicular to the accelerator axis. During transient process of accelerating field setup in resonators, as on the trailing edge of HF pulse envelope, electromagnetic field exists in CIW section. At typical parameter values: $P_g = 1\ MW, {}^{d}/_{\lambda} = 0.038$ (where λ is the generator wavelength, d is the orifice thickness) the maximum intensity of electric field at the axis of accelerating section is $E_0 \cong 40\ kV/cm$.

During transient process upon passage across CIW, the main bulk of electrons is cutoff, which previously after accelerating in non-optimum electric fields impaired significantly spectral properties of the facility. Therefore, the considered HF systems permit simultaneous improvement of spectral properties of standing wave linac and increase ni their operation efficiency.

4. CONCLUSIONS

In the considered high-frequency systems complete decoupling of generator from high-Q accelerating sections is achieved, the influence of current load by accelerating sections decreases, and beam output properties are improved.

Such systems permit fine tuning of HF energy supplied to accelerating resonator sections and simultaneous variation of time constant of transient process of electric fields setup in the sections.

We plan to consider designs of coupling cells and input unit of high-frequency power of standing wave linac, which would permit tuning of accelerating current with optimum mode of electron acceleration and tuning adjusting of beam output energy at fixed value of accelerating current.

Embedding of apparatuses enabling wide range tuning of parameters of accelerating beam without degradation of its quality into accelerating and high-frequency systems makes it possible to solve successfully numerous experimental and practical tasks by means of similar devices. Such universalization would provide possibility to arrange serial production and successful implementation of accelerators of this type.

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REFERENCES

Filatov A.N.,Shilov V.K. 1985. Control of radio-frequency characteristics of linear electron accelerator. Instruments and Experimental Techniques New York, Volume 28, Issue 6 pt 1, November, pp. 1258-1261.

Filatov A.N., Shilov V.K. 1984.RF Focusing in the Standing-Wave Electron Linacs, Soviet physics. Technical Physics. 29(2): 163-167.

Ginzton E. L. 1957. Microwave Measurements. New York: McGraw-Hill.

Helszajn J. 1978. Passive and Active Microwave Circuits. John Wiley and Sons Inc.

LebedevI. V. 1972. Microwave Technology and Instruments. Moscow: Vysshaya Shkola.

Novozhilov A.E., Filatov A.N. Shilov V.K. 2016. Calculation of Resonant Frequencies and Electromagnetic Fields in Resonators of Linear Accelerators for Commercial Application, Medicine and Environmental Protection. Research Journal of Pharmaceutical, Biological and Chemical Sciences. 7(2): 897-905.

Novozhilov A.E., Filatov A.N., Shilov V.K. 2014. Assessment of method errors in measurement of acceleration fields in accelerating sections of chargedparticle accelerators. Life Science Journal. 11(11s): 506-510. DOI:10.7537/marslsj1111s14.115.

NovozhilovA.E. etal. 2016.Problems of measurement of high-frequency fields in linear electron accelerators, Global Journal of Pure and Applied Mathematics, 12(1): 643-655.

Vikulov V. F., Zavadtsev A. A., Zverev B. V., *et al*. June 1979. A Compact Standing-Wave Electron Linac with RF Drive System Using 3 dB Hybrid Junction. IEEE Transactions on Nuclear Science. NS-26(3): 4292- 4293.

Vikulov V. F., Zavadtsev A. A., Zverev B. V., *et al*. 1979. Standing Wave Electron Linac with Bridge power Circuit for Defectoscopy and Medicine. Proceedings of III All-Union Meeting on Application of Charged Particle Accelerators in National Economy. Leningrad: NIIEFA. pp. 186-195.

Vikulov V. F., Zavorotylo V. N., Ruzin V. V. 1982. Improvement of energy spectrum in standing wave accelerators by means of delayed injection. ZhETF. 52(11): 2188-2191.