Emission Gated Device Issues
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Abstract—The requirement for high efficiency, high power RF sources in a compact package has suggested the use of a pre-bunched electron beam. In a gated emission device, the beam is bunched in the electron gun region prior to acceleration and transport into the RF extraction region. In this paper we review the basic dynamics of bunch formation and describe the gating technologies currently available for the production of a pre-bunched beam. Considerable insight into the basic physics of emission gating, such as beam dynamics and frequency spectra, is obtainable from numerical modeling. Some unresolved issues are presented for investigation.

I. BACKGROUND

A review of linear and nonlinear analyses applicable to emission gated devices is provided in this section with an explicit declaration of the physical assumptions for each model. This paper considers density gating, not velocity modulation, emphasizing high-power and high-efficiency applications.

An expectation of increased efficiency through the use of density gating for the RF input bunching of an electron beam is provided by the following analysis. We define a maximum possible efficiency as

\[ \eta = \frac{F_1}{F_0} \]

where

\[ F_1 = \frac{\omega}{2\pi} \int_0^{\pi/\omega} I V \exp(-j\omega t) \, dt \]

\[ F_0 = \frac{\omega}{2\pi} \int_0^{\pi/\omega} I V_0 \sin(\omega t) \exp(-j\omega t) \, dt \]

which give values, \( \eta = 58\% \) and \( \eta = 82\% \) respectively. At high frequencies, transit-time effects can distort the Class B current waveform into a sawtooth profile

\[ I(t) = \begin{cases} I_0(1 - \omega t/\pi), & 0 < \omega t \leq \pi \\ 0, & \pi < \omega t \leq 2\pi \end{cases} \]

which gives a value, \( \eta = 75\% \) is obtained. Even then, a relatively high value, \( \eta = 75\% \) is obtained. These values for \( \eta \) are indicative of the relatively high efficiencies which may be possible with gated emission devices.

The theoretical basis for electron flow in a diode has proceeded historically from the steady-state case toward increasing RF frequency. The electron inertia must be included as the accelerating field increases in frequency and magnitude. As the period of the applied voltage approaches the time required for an electron to travel from the cathode to the grid (the cathode-grid transit time \( T \)), the electrons may oscillate in the cathode-grid region many RF periods before either escaping through the grid or returning to the cathode. This transit-time effect limits the performance of the device to frequencies determined by how close to the cathode the grid may be placed within practical construction constraints. Theoretical analysis of large amplitude modulation such as the current waveforms discussed above (Class B and C) cannot be carried out by a small signal perturbation approach. Such an analysis requires the use of a nonlinear particle-type model.

The inclusion of a grid structure near the cathode surface allows a voltage to control the current emitted from the cathode. An analytical solution for triode geometries may be derived using a conformal mapping technique (see, for example, Gewertowski and Watson [1, Appen-
A linear combination of two potential functions describes the combination of grid-cathode and anode-cathode potential fields

$$V(x) = V_{G\text{c}}G_1(x) + V_{A\text{c}}G_2(x).$$

The Green's function $G_1(x)$ is the potential function with the cathode and anode held at ground and the grid set at $1\text{ V}$ for the given geometry; similarly, $G_2(x)$ is the potential function with the cathode and grid held at ground and the anode set at $1\text{ V}$ as shown in Fig. 1. A figure of merit for a given geometry is a ratio of the gradients of these Green's functions evaluated normal to the cathode surface, the electrostatic amplification factor $\mu_{es} = \frac{\partial V_{G\text{c}}}{\partial \gamma_c}/\left[\frac{\partial V_{A\text{c}}}{\partial \gamma_c}\right]_{\text{c}}$. Equivalently, $\mu_{es} = -\frac{\partial V_{A\text{c}}}{\partial V_{G\text{c}}}$. The electrostatic amplification factor is a measure of the relative effect on the creation of a normal component of the electric field at the cathode due to the application of voltage at the grid and anode. This can be displayed by inserting the definition of $\mu_{es}$ into the gradient of the potential

$$\frac{\partial V}{\partial \gamma_c} = \frac{\partial G_1}{\partial \gamma_c} \left(V_{G\text{c}} + \frac{V_{A\text{c}}}{\mu_{es}}\right).$$

The normal operating condition for a triode is space-charge limited to allow the grid to be effective in controlling the current. The static behavior as displayed by characteristic curves of anode current as functions of anode and grid voltages can be parameterized by two quantities, the transconductance $g_{m} = \frac{dI_{A\text{c}}}{dV_{G\text{c}}}|_{v_{G\text{c}}}$ and $\frac{dI_{A\text{c}}}{dV_{G\text{c}}}|_{v_{G\text{c}}}$, and the dynamic anode resistance $r_{a} = \frac{dV_{A\text{c}}}{dI_{A\text{c}}}|_{V_{G\text{c}}} = \frac{dV_{A\text{c}}}{dI_{A\text{c}}}$. The amplification factor $\mu$ is given by the product $g_{m}r_{a}$ and may be expressed in differential form

$$dI_{A\text{c}} = g_{m}dV_{G\text{c}} + r_{a}^{-1}dV_{A\text{c}}$$

and a variation of parameters such that $dI_{A\text{c}} = 0$ yields $\mu = -\frac{dV_{A\text{c}}}{dV_{G\text{c}}}|_{V_{G\text{c}}}$ which is very similar to the electrostatic amplification factor $\mu_{es}$. The inclusion of space charge is readily achieved by the solution of the Poisson equation for the potentials (or equivalently, by enforcing charge continuity) in either the static or dynamic case.

Realistic grid geometries, grid interception, and periodically interrupted electron flow may be included in particle models. The use of digital computation for the study of the motion of electrons in vacuum electron devices dates back to the 1940's with the work on magnetrons by Hartree and Buneman and on the traveling-wave tube by Nordsieck. The use of the Particle in Cell (PIC) simulation method is particularly effective for vacuum electronic device simulation [2] because the fundamental Maxwell and Newton-Lorentz equations are used to calculate the particle-field interactions. The evolution of the beam-wave coupling can be studied from the linear to the completely nonlinear regime, i.e., both small- and large-signal processes are included. In contrast to analytical theory, realistic boundary conditions are readily incorporated. Similarly to experiment, diagnostics can be used to measure nonintrusively field quantities, particle distributions, and the Fourier spectra in both space and time of these quantities. Simulations can be run for many different sets of parameters and may thus be able to provide not only numbers but to assist in the development of intuition.

The system evolves from a set of initial conditions with due consideration of spatial boundary conditions. Many of the limitations of PIC modeling are due to the accuracy with which boundaries may be modeled. For example, to accommodate boundaries with large curvature as in field
emitter structures, the cell dimensions may be quite small. Numerical stability then requires the use of a small time-step. This constrains the physical time which may be simulated and may make the examination of slow time scale processes impractical without further approximation.

If charge continuity is satisfied, the electrostatic fields may be obtained from an initial Green's function solution of the Laplace equation once and then the combined Ampere and Faraday equations are sufficient to characterize the field evolution and RF characteristics (i.e., Poisson's equation is then automatically satisfied at any time). The simulations presented in this paper were done using the two-and-one-half-dimensional electromagnetic PIC code MAGIC [3]. The simulation of space-charge-limited electron emission produces electrostatic current-voltage curves (Fig. 2) in agreement with the experimentally measured quantities for the benchmark WE417A triode, which is discussed in depth by Gewartowski and Watson [11].

A proposed gridded diode design was simulated to ascertain the variation in efficiency as a function of frequency. The beam coupling coefficient sin \((\omega T/2)/(T/2)\) is insufficient to fully describe the field–beam interaction for Class B and C nonlinear operation in this device. The frequency dependence from PIC simulations, which include the space-charge and nonlinear effects, is shown in Fig. 3 where the anode current as a function of time is displayed for 300 MHz and for 2 GHz. The distortion of the current towards a sawtooth shape at the higher frequency is apparent. An efficiency of \(~75\%\) was, however, observed for both cases and the efficiency did not fall off appreciably until above 2 GHz. The beam current spectrum at the anode plane is displayed in Fig. 4 and shows the increased higher order mode amplitudes at 2 GHz.

II. FIGURE OF MERIT FOR WIDE-BAND PERFORMANCE

The use of figures of merit, such as gain–bandwidth product, phase shift, maximum power determined by saturation or thermal loading, isolation between the input and output signals, device efficiency, and capacity for Class A, B, or C operation, helps to determine the suitability of competing devices for a particular application. It is desirable to compare the active devices alone by removing variations in amplifier network performance that result from variations in the device couplings while recognizing that the input and output impedances may be a determining factor in device selection. The gain–bandwidth prod-
uct of an amplifier is the most widely used figure of merit. This parameter is the theoretical maximum bandwidth over which unity gain is possible between equal input and output impedances [4]. The compromise between gain and bandwidth is closely related to the compromise between gain and efficiency. A low Q or nonresonant output circuit must have weaker beam-to-circuit coupling which leads to lower electronic efficiency. Practical amplifier circuits add additional losses that reduce performance to about 50% of the tube's bandwidth index.

It is well known [5] that the voltage gain between equal impedances is given by

\[ A = \frac{-g_m}{|j\omega C_g + G_{in}|} \text{ and } \frac{-g_m}{|j\omega C_p + G_L|} \text{ for } G_{in} \text{ and } G_L \text{ respectively.} \]

Thus for klystrons, klystrodes, and multigrid tubes the product of voltage gain and frequency is a constant. Since the input capacitance varies as the inverse of the grid-cathode spacing, but the transconductance as the inverse squared, the performance of gridded tubes improves as the grid–cathode spacing is reduced. Thus grid materials and fabrication techniques have limited the high frequency performance (Section IV). In gridded triodes, as commonly employed, the input circuit Q is negligible compared to that of the output (\(G_{in} \gg j\omega C_g, G_L \ll j\omega C_p\)), giving

\[ |A|f = \frac{-g_m}{2\pi G_{in} C_p}. \]

To obtain still greater maximum bandwidth, gridded TWT’s, such as the NRL Emission Gated Device Experiment [6], employ traveling-wave output couplers typically of much lower Q than that of the input circuit (\(G_{in} \ll j\omega C_g, G_L \gg j\omega C_p\)) giving

\[ A^2f = \frac{-g_m^2}{2\pi G_L C_g}. \]

Thus where only one resonant circuit is present the product of power gain and frequency is a constant of merit. Distributed amplifiers have nonresonant input and output circuits [7]. As above, the gain due to each discrete tube is

\[ A = -g_m (Z_m Z_0) /\sqrt{C_s C_p}. \]

For \(n\) discrete tubes coupled by low-pass \(LC\) filter sections the net gain is

\[ |A_n| = -ng_m (L_s I_p /\sqrt{C_s C_p})^{1/2}. \]

neglecting circuit losses. If gate losses, which vary as \(n^2\), are included, an optimum value of \(n^*\) exists [8]. To first order, the gain is independent of frequency. The bandwidth of distributed amplifiers is limited by cathode losses, i.e., cathode lead inductance and transit-time effects.

The bandwidth of photocathode devices is determined by the output circuit, provided that space-charge debunching in the acceleration region is not excessive. There is no transit-time limitation in the input region since the electrons never move under the influence of an oscillating electric field, however, space-charge debunching in the acceleration region limits the useful perveance.

When any figure of merit is employed, its range of validity must also be noted. Taking a triode for example, the ratio \(g_m / \sqrt{C_s C_p}\) ignores lead inductances which cause heavy losses at high frequencies.
III. Devices

The classical high-frequency vacuum tube reached maturity in the late 1940’s with the “lighthouse” family of cavity driven, gridded tubes [9]–[12]. The lighthouse design minimized parasitic losses by making all high-frequency connections radially through disc leads. The 416A achieved 10-dB gain at 4 GHz with 2.5% instantaneous bandwidth. Further advances in the gain–bandwidth product in this geometry required cathode–grid spacings of less than 0.2 mil (0.05 mm). Efforts to improve the high-frequency efficiency encountered the same fabrication limit due to transit-time effects in the grid–cathode space, while power handling was limited by current interception on the fragile grids. Subsequent development shifted to velocity-modulated (klystron, TWT) and crossed-field devices. Today, novel techniques and improvements in materials and fabrication technologies have motivated a review of many proposals once dismissed as unrealizable.

Emission gated tube development since the lighthouse tube has proceeded toward several distinct objectives:

1) Increase the power by employing a large cathode area in parallel and a high Q, efficient output cavity, in a simple trade of bandwidth for high average power. The “Resnatron” [13]–[16] was a multibeam tetrode in the form of two coaxial cavities 1/2 or 3/4 wavelengths long. As seen in Fig. 5, the cathode was arranged in axial strips on the innermost cavity wall and the electrons from each strip, electrostatically focused, flowed radially outward between the bars of the nonintercepting grid and screen electrodes to be collected on the anode. Power output of more than 60 kW CW with 40–70% anode efficiency and 10-dB gain was commonly obtained. Mechanical tuning was possible over an octave in the UHF band. Resntron development was dropped due to low power gain and a small instantaneous bandwidth.

The “Martotron” was proposed by Bekhtev et al. [18] to meet a need for a highly efficient linac driver but was not selected for implementation. The input and output circuits are toroidal cavities of square cross-section, in which input and output signals of equal phase velocity propagate azimuthally, coupled by an 80-kV, thin annular beam propagating axially. The electron beam is excited by the input traveling-wave resonator in which the \( H_{04} \) mode is excited. This azimuthal propagation of the RF implies an integral number of wavelengths in the circuits, again sacrificing bandwidth for improved gain. Efficiencies of 80% were predicted in its operation by properly phasing the output wave.

2) Increase gain and bandwidth by distributing the electrodes along a transmission line. A distributed amplification circuit was proposed by Ginzton et al. [7]. By employing conventional high-frequency tubes as shunt admittances coupling a pair of transmission lines, the net transconductance is increased without a corresponding increase in shunt capacitance. A wave propagating in the input transmission line excites the input circuits of the tubes: RF power extracted in the output circuits propagates in the output transmission line (Fig. 6). The RF signals from each tube add in phase in the forward direction; in an ideal circuit no power flows in the reverse direction. The unused transmission line ports are terminated in the characteristic impedance to provide nonresonant input and output circuits. Horton et al. [19] considered the effect of high frequency losses on distributed amplifier circuits and found that the cathode lead inductance became the limiting factor. Solid-state distributed amplifiers have been reported in the literature [19]. Continuous distributed amplifiers have been proposed in which the grid–cathode and grid–anode spaces form parallel-plate input and output transmission lines. Ganguly et al. [20] have developed a small signal theory of proposed microelectronic field emission distributed amplifiers. Such a design incorporates a microstrip transmission line with field emitter structures. They suggest that 7-dB/cm gain at 50 GHz with a 60% instantaneous bandwidth may be obtained with an optimized design.

3) Increase power and/or bandwidth by separating the RF output circuit from the beam collection electrodes. In practice, efficiency and isolation are also improved because the kinetic energy of the beam is converted directly to RF. In the “Inductive Output Tube,” Haeff and Nagard [21] achieved 10-W output at 500 MHz, with 2% bandwidth, 10-dB gain, and 25% efficiency. The project was dropped because of the low power handling ability of the grid. The modern version of Haeff’s tube, the klystrode™ of Preist and Schrader [22], employs a laser-machined, pyrolytic graphic grid. In the schematic shown in Fig. 7, the location of the grid, at device scale, is indistinguishable from the cathode surface. At 775 MHz they obtained 20-kW power output for 21-dB gain and a bandwidth of approximately 0.25%, with 32.3-kW power output for pulsed operation. Their X2251 klystrode [23] at 785 MHz had a bandwidth of 8 MHz with 32-kW power output at an efficiency of 48% and at 470 MHz for 20-kW output the measured efficiency is over 70%. The klystrode...
is in use as a television signal amplifier. In this application the commercial advantages and disadvantages of the klystron are the high efficiency and the nonlinearity, respectively, resulting from Class B operation to reduce the dc power load on the grid.

The RF extraction region does not necessarily have to be a cavity. Analysis and experiments with traveling-wave output circuits are discussed in Section VI.

4) Increase bandwidth by removing the cathode–grid input capacitance by eliminating the grid and substituting alternative means of bunched beam production. Photocathodes may be used for emission gating in applications such as free electron lasers where very high beam brightness is required [24]. Laser pulses can be modulated at microwave frequencies to produce tailored current waveforms for maximum efficiency. Emission gated photocathodes have the advantage that the electric field at the cathode surface is dc: the upper limit of bandwidth is set by the space-charge spreading of current bunches, not by conventional transit-time effects.

IV. THE INPUT CIRCUIT: EMISSION GATING OPTIONS

A closer look at the technical advances which enable the application of emission gating to the high-frequency, high-power regime is appropriate. The creation of a density bunched beam by gridded cathodes, field emission cathodes, and photo-emission cathodes is considered in this section.

Grid-controlled cathodes are limited in high-frequency response by transit-time effects, high grid–cathode capacitance, and low transconductance. The spacing of the grid–cathode gap and the transparency of the grid are critical fabrication limitations. At common operating voltages and frequencies above 1 GHz, structures smaller than 10 μm must be fabricated to 10% tolerance or less. Grid materials must possess good thermal and electrical conductivity, excellent mechanical stability at high temperatures, and low secondary electron emission ratios. The most common materials meeting these requirements are tungsten or molybdenum, possibly coated with noble metals. Graphite, an early contender which was dropped because of excessive fragility, has returned in the form of pyrolytic graphite.

The grid of the 416A triode operating to 4 GHz is 90 mil (2.3 mm) in diameter, fabricated of 0.3 mil (7.6 μm) tungsten wire wrapped 1000 turns-per-inch, and is mounted 0.6 mil (15 μm) above the cathode surface. Variations in wire spacing and grid–cathode spacing was less than 10%, although the cathode diameter was 150 times the grid–cathode spacing. If the 416A cathode were scaled up to the size of a desktop, the grid separation would be about the thickness of a pencil, and its deviation from flatness less than the thickness of five sheets of paper. Measurements indicated that the 416A is within a factor of five of the theoretical maximum performance imposed by the thermal velocity spread of electrons emitted by a thermionic cathode. The most severe limitation in this line of development is the power-handling capability of the grid structure. The cathode size is limited by the stiffness of the grid wires and the maximum current density (180 mA/cm²) by the return current. The 416A provides 8 dB of gain at 50-mW output power.

Pyrolytic graphite is a superior material for grid construction. It is the strongest refractory element, three times the strength-to-weight of tungsten at 1000°C. It is produced by a chemical vapor deposition process [25]–[27]. The carbon precipitates onto a polycrystalline graphite mold of almost arbitrary shape, but strongly concave surfaces cannot be coated. The desired grid lattice is usually cut out of the pyrolytic graphite shell by laser machining in air. Unlike common graphite, pyrolytic graphite is highly anisotropic. The thermal and electrical conductivities of the finished grid are much higher parallel to the surface than through it. In a 500-kW, 26-MHz tetrode, a pyrolytic graphite grid provided twice the power dissipation of an equivalent coated molybdenum grid [28]. In addition, thermal expansion occurs primarily perpendicular to the surface: a pyrolytic graphite grid thickens in heating proportionately more than it increases in radius (see Table I).

Pyrolytic graphite grids are manufactured to tolerances and uniformity exceeding those of refractory wire grids. In a detailed comparison of pyrolytic graphite with coated molybdenum wire for service in a high-power, short-wave frequency tetrode, tubes manufactured with graphite grids gave superior and more uniform performance [28].

Field emission grid–cathode structures smaller than the 416A may provide large total currents. In one approach, solid-state fabrication techniques are used to grow conical emission tips of semiconductor or refractory metal materials on a silicon substrate [29]. A refractory metal gating electrode is supported by a layer of insulator. Electrons are emitted from the surface in response to extremely high fields which are created by the grid at the emission tip. The electrons' momenta carry them quickly out of the strong field region where they are captured by the anode field and accelerated away from the field emission structure. The separation of the emitting surface from the control electrode is of the order of 1–5 μm, combined with field strengths greater than 10⁹ V/cm, which suggests that transit-time effects will be insignificant to tens of gigahertz. Capacitive loading is a matter of some concern since the separation of the grid from the semiconductor substrate is less than 10 μm. Transconductances greater than 60 S/cm² have been observed in low-frequency experi-
ments [30]. The transconductance itself may prove to limit the high-frequency performance of field emitter cathodes, as realistic input impedances will be extremely small. Work has begun at NRL to develop a field emitter assembly that is optimized for high-frequency operation, primarily in geometric adaptations to reduce the grid-cathode capacitance.

Photocathodes can have very low thermal spread, contributing to a desirably low emittance. The 30% quantum efficiency [31] of this cathode must be combined with the efficiency of the laser which yields an overall low efficiency which is however acceptable for some applications.

V. THE OUTPUT CIRCUIT: RF POWER EXTRACTION OPTIONS

Any power extraction circuits used in conventional klystron or traveling-wave devices may be employed as output circuits for a prebunched electron beam. The primary difference in performance will be due to the superior beam modulation and reduced velocity modulation induced by a gridded input compared to bunching by velocity modulation. As the frequencies push into the microwave regions, the power which can be dissipated in an integral anode-collector becomes a major limitation. By separating the functions of RF power extraction from electron beam collection, each function may be further optimized. A high-Q output cavity provides narrow-band service at desirably high efficiencies [32], [33]. An output circuit employing a traveling-wave interaction may be used where increased bandwidth is a consideration.

While the gain and bandwidth of an emission gated device are influenced by both the input and output circuits, the efficiency is primarily dependent on the output circuit. Bunching the beam requires little energy; losses in the input section are limited to heater power and grid interception current. (Laser-driven photocathodes are an obvious exception.) The greatest losses occur when the energy of the accelerated beam is wasted in the output and collection regions. Simulations of traveling-wave and cavity output circuits [32], [34] agree that the highest efficiencies may be obtained in Class C, i.e., when the bunched beam is confined to as little as 20° of the RF cycle. In these conditions, space-charge spreading of the bunches becomes a concern at comparatively low beam currents.

In Section III a number of emission gated devices employing resonant cavity outputs have been briefly reviewed. All of these were proposed and/or constructed for applications which place a premium on efficiency over bandwidth, such as linear accelerator drivers, commercial television, and space-based RF power systems. The efficiency advantage of resonant output circuits derives from the ease with which strong, properly phased RF fields can be concentrated in the beam region. With careful design efficiencies in excess of 70% may be realized in this class of devices.

The use of traveling-wave output circuits for emission gated devices has been explored theoretically and experimentally. Rowe [35], [36] examined the linear and nonlinear coupling between bunched beams and propagating circuits. Linear theory identified two amplification mechanisms operating in distinct regimes of relative beam velocity: the conventional TWT amplification to the growing wave and a second, three-way interaction of the beam and the slow and fast circuit waves occurring at such high relative beam velocities that no growing wave exists. The nonlinear simulations yielded a significant improvement in efficiency: 52% for a prebunched beam 20° in width versus 7.6% for an equivalent unbunched TWT. Lichtenberg [34] conducted an instrumented experiment which demonstrated linear growth of the circuit wave on a helix excited by a prebunched beam, while an unbunched beam yielded an initially slow exponential growth. In that experiment velocity modulation was superimposed to counteract debunching by space-charge forces, however, residual velocity modulation in the spent beam was larger than expected. The NRL Emission Gated Device Experiment [6] will be employed to examine beam-to-circuit coupling over a wide range of beam parameters. Relative injection velocities spanning the boundary between exponential growth and three-wave amplification will be used. A three-way beat wave interaction can be identified by its very strong variation with injection velocity, in contrast to the broad gain maximum of a conventional TWT. Sources of velocity modulation on the beam will be examined through the relation of experimental diagnostics to ongoing simulation and theoretical studies.

VI. CONCLUSIONS

An emission gated device has its beam density bunched in the electron gun region prior to acceleration and transport into the RF extraction regions. An analytical treat-
ment of the bunching process from first principles is made difficult as the beam modulation is increased into the large-signal regime. Analysis by perturbation techniques fails when the beam is chopped, the most interesting operating condition. Computational models are thus required to access this regime. Such models are in common use and provide good agreement with experiment. Various types of high-frequency amplifiers employing prebunched electron beams, with suggestions for their competitive evaluation for applications requiring large bandwidth, high power, or other advantages have been discussed herein. Comparison of the gain-bandwidth figure of merit of devices employing two, one, or no resonant circuits shows the motivation for new, high-transconductance electron sources employing technology such as pyrolytic graphite grids and field emission cathodes to extend the performance envelope of density gated devices. A program underway at NRL is exploring new techniques for beam bunching, including field emission structures, and the behavior of prebunched beams in broad-band output circuits.

ACKNOWLEDGMENT

The authors wish to acknowledge helpful discussions with N. R. Vanderplaats.

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