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GYROTRONS: USING RELATIVISTIC ELECTRONICS TO PRODUCE HIGH POWER, HIGH EFFICIENCY, MILLIMETER-WAVE SOURCES*

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Introduction

Gyrotrons emit coherent radiation at the electron cyclotron frequency. Basically, they have been capable of unusually large power levels at short wavelengths because the resonant wavelength is fixed by the strength of an externally applied magnetic field rather than by the scale of a circuit structure as in most conventional tubes. Hence, in principle, one can more successfully employ circuits with larger dimensions which are capable of handling higher power levels. The gyrotron circuits moreover are uncomplicated and inexpensive, usually consisting simply of an unloaded circular waveguide or of a cavity formed by using a length of such a waveguide with end reflectors.

The process of wave amplification in gyrotrons is attributable to phase bunching of the electrons in their cyclotron orbits. The electron cyclotron frequency is given by $\Omega_c = eB_0/m\gamma$ where e is electron charge, m is electron rest mass, B_0 is the applied d.c. axial magnetic field, and γ is the relativistic energy factor. Because Ω_c depends on γ, electrons whose phase relative to an electromagnetic wave leads to deceleration, experience an increase in Ω_c and advance in phase in their cyclotron orbits. On the other hand, electrons which are accelerated accumulate phase lag. The net result is a phase bunching which favors wave amplification if the wave frequency is slightly larger than the cyclotron frequency in the reference frame where axial electron velocity, $v_{\parallel}$, vanishes. Thus, the mechanism responsible for gyrotron wave amplification is relativistic in nature. Research studies of this mechanism both theoretical[1-4] and experimental[5-7] began over two decades ago. Those studies have now led to the development of a new class of millimeter wave oscillator which constitute a closing of the 'gap' in the electromagnetic spectrum at millimeter wavelengths where high power sources have been previously unavailable.

In Fig. 1, the reported power levels in long pulse ($\geqslant$ 0.1 millisecond) gyrotron oscillators are plotted as a function of frequency. It is clear that power levels orders of magnitude above the capabilities of conventional microwave tubes have been achieved throughout the millimeter waveband (1-10 mm). All the data points in Fig. 1 come from experiments at the Institute of Applied Physics in Gorky[8] except for the two open square data points. The data point at 28 GHz represents the achievement by Varian Associates of 212 kW cw power,[9] by far the largest cw power achieved to date with gyrotrons or for that matter with any tube type at frequencies near the millimeter waveband.

The open square data point at 35 GHz represents a 150 kW gyrotron oscillator operated at the Naval Research Laboratory, NRL, with 20 msec pulse duration.[11] This gyrotron has been applied to electron cyclotron resonance heating (ECRH) of the plasma in a large Tokamak device at the Oak Ridge National Laboratory.[12] Results of the heating experiment were impressive. Approximately 60% of the gyrotron power was absorbed by the plasma, with projection of virtually complete absorption in a Tokamak of reactor size.

While gyrotron oscillators are the preferred gyrotron configuration for energetic applications such as plasma heating, there has also been interest in developing gyrotron amplifiers because of the potentially superior characteristics in information-carrying systems such as communication links and radars. Among the amplifier advantages are substantial instantaneous bandwidth, ability to generate complex waveforms, flexibility in signal modulation, and ability to control the phase and frequency of the signal. However, gyrotron amplifier experiments are in a preliminary state when compared with the extensive study that has been carried out on gyrotron oscillators.

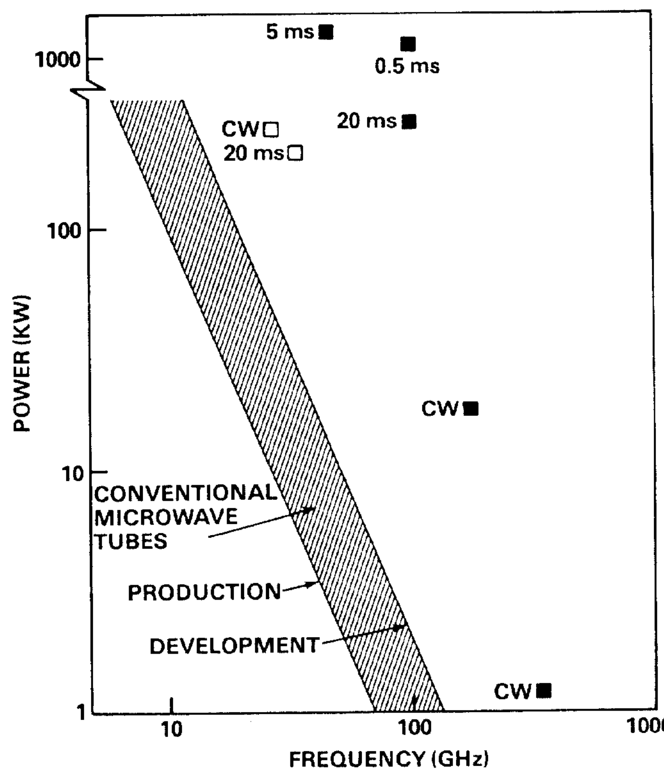

Fig. 1 — CW and long pulse microwave tube state-of-the-art 1980. (■ Gyrotrons developed at the Institute of Applied Physics, Gorky, U.S.S.R; □ Gyrotrons operated in the U.S.A.) (reproduced from Reference 10).

Gyrotron Traveling-Wave Tube Amplifiers

The gyrotron traveling-wave tube amplifier[13] (gyro-TWT) utilizes a simple waveguide circuit with a fast-wave propagating mode to interact with the fast cyclotron wave of the electron beam. This electron beam consists of mildly relativistic electrons spiraling in cyclotron orbits and drifting axially down the waveguide. The beam is usually annular as produced by a magnetron injection type electron gun, with annular radius, r_0, much larger than the Larmor radius, r_L.

The gyro-TWT interaction stems from a waveguide mode whose characteristic equation is

$$\omega^2 - k_z^2c^2 - \omega_{c0}^2 = 0 \qquad (1)$$

interacting with a beam cyclotron mode with a charactertistic equation

$$\omega - k_z v_{\parallel} - s\Omega_c = 0 \qquad (2)$$

where ω is the signal frequency, ω_{c0} is the cutoff frequency of the mode of interest, k_z is the axial wavenumber, c is the speed of light in vacuum, and s is the cyclotron harmonic number. For high gain and efficiency the two characteristic curves are adjusted near grazing intersection such that the phase velocities of the two modes are nearly matched and the group velocity of the waveguide mode is nearly equal to $v_{\parallel}$. Derivations of the complete dispersion relation describing the coupling of the beam and the waveguide modes appear in the literature.[14-16]

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The temporal growth rate for circular TE^0_{mn} modes and for a cold electron beam has been found by solving the dispersion equation for the imaginary part of the frequency,[14] yielding

$$\omega_i = \left[\frac{3^{3/2} \nu x_{mn}^2 H_{sm} \beta_\perp^2 c^4}{4 \gamma K_{mn} \omega r_w^4} \right]^{1/3} \tag{3}$$

where $\nu = I r_e / e v$ (I is the electron beam current, and $r_e = 2.8 \times 10^{-13}$ cm is the classical electron radius), $\beta_\perp = v_\perp / c$ ($v_\perp$ is the electron perpendicular velocity), and x_{mn} is the nth root of $J_m'(x) = 0$.

H_{sm} and K_{sm} are defined as follows:

$$H_{sm} = [J_{s-m}(x_{mn} r_0 / r_w) J_s'(x_{mn} r_0 / r_w)]$$

where r_w is the waveguide radius;

$$K_{mn} = J_m^2(x_{mn}) [1 - m^2 / x_{mn}^2].$$

Note that, by Eq. (3), the electrons are required to have a non-vanishing perpendicular velocity or else no wave growth takes place. Near the point of grazing intersection the spatial growth rate Γ is given by

$$\Gamma \cong \omega_i / v_\parallel \tag{4}$$

and the total power gain in decibels is

$$G = -10 \log_{10} 9 + 8.686 \, \Gamma L. \tag{5}$$

Equation (5) is valid for $\Gamma L > 1$ where L is the length of the amplifying region.

The circular waveguide mode which is capable of the largest gain per unit length for fundamental cyclotron operation is the circularly polarized TE^0_{11} dominant mode.[17,18] There is preliminary experimental evidence that gyro-TWT amplifiers become degraded in saturated efficiency as the interaction structure becomes long; this may be an effect of beam velocity spread. In that case, for a given total gain and beam velocity spread the TE^0_{11} mode requires a shorter amplifier length and thus is expected to yield a greater efficiency than the higher order modes such as TE^0_{0n}. Also, employing a higher order mode involves greater complication in launching the mode and in maintaining mode purity. However, for very high-frequency, high-power applications, circuit losses become excessive for the TE^0_{11} mode and lower loss modes such as TE^0_{01} become the preferred choice.

The first purposeful experimental demonstration of the gyro-TWT amplifier was carried out at NRL using an intense relativistic electron beam.[19] This experiment led to a program of the development of more practical gyro-TWT's at 35 GHz.[20-22] The 35 GHz experiments have employed the TE^0_{01} mode and an interaction waveguide with $r_w = 5.33$ cm corresponding to $\omega_{c0} = 34.3$ GHz. The electron gun was a magnetron-injection type[23] designed to produce an annular electron beam of guiding center radius 2.5 mm with $v_\perp = 0.40\, c$, and a $v_\parallel = 0.27\, c$, corresponding to a beam energy of 70 keV. As is usual with gyrotrons, the electron gun was operated temperature limited to minimize velocity spread. The design velocity spread $\sigma(v_\parallel)/\bar{v}_\parallel \approx 8\%$ where $\sigma(v_\parallel)$ and $\bar{v}_\parallel$ are respectively the standard deviation and the mean of the electron distribution in $v_\parallel$. The most recent NRL gyro-TWT experiments[21,22] use an input coupler which is a TE_{01}-coaxial-mode to TE_{01}-circular-mode junction developed for that purpose.[24] This coupler is depicted in the amplifier schematic of Fig. 2. The overall length of the interaction waveguide (the inside of the coaxial inner wall) is 21 cm. The magnet is a superconducting solenoid system with an axial magnetic field profile as illustrated.

Gain curves that were obtained by plotting the output rf power as a function of input drive power at several beam currents are shown in Fig 3. For beam currents of 9 amps, 3 amps, and 1 amp, gains obtained were 32 dB, 24 dB, and 12.5 dB, corresponding to linear growth rates of 0.23 cm^{-1}, 0.18 cm^{-1}, and 0.12 cm^{-1}, respectively. The growth rate scales as $\Gamma \sim I^{1/3}$ as predicted by theory (Eq. 3). Saturation begins at approximately 10 kW for the 9 amp case with 30 dB gain. The highest efficiency obtained was 7.8 percent at 16.6 kW output with 20 dB gain for a 3 amp beam current.

Figure 4 shows the small signal bandwidth measurement at a beam current of 3 A. The 3 dB bandwidth (FWHM) is approximately 1.4% with useful gain having a much wider extent. The solid curve in Fig. 4 is a theoretical prediction made by K. R. Chu on the basis of growth rate calculations for a Maxwellian distribution of electron velocities;[21]

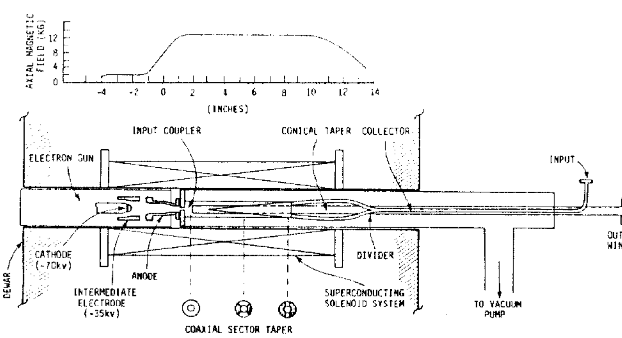

Fig. 2 — A gyro-TWT for 35 GHz operation in the TE^0_{01} *mode. Figure is reproduced from Reference 24.*

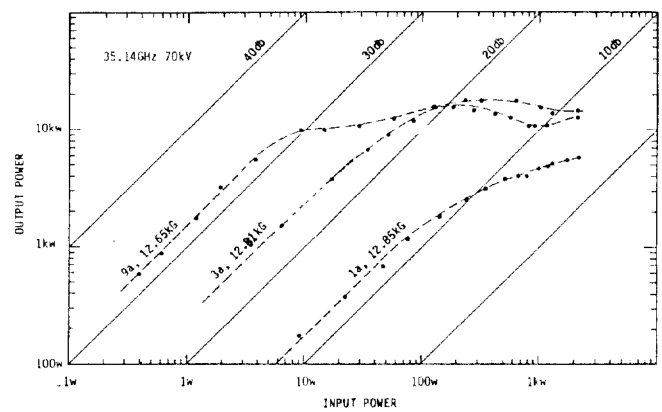

Fig. 3 — Typical amplifier gain curves for several values of beam current. The magnetic field was adjusted for optimum linear gain. These curves are an update of a figure which appeared in Reference 21.

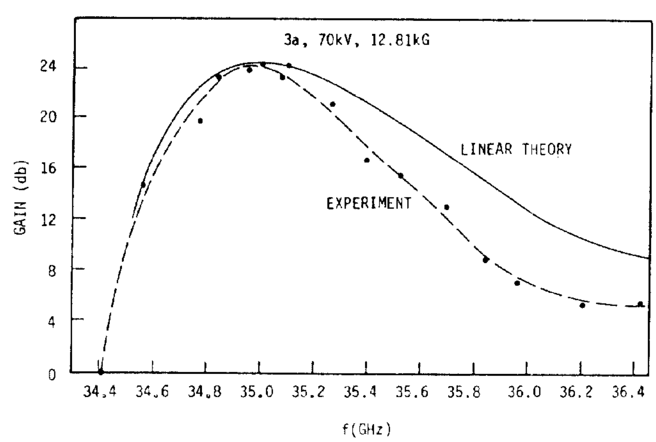

Fig. 4 — Small signal bandwidth measurement for the TE^0_{01} *gyro-TWT. Figure reproduced from Reference 21.*

the absolute value of the peak gain is in excellent agreement with the experimental data while the predicted bandwidth is somewhat larger than measured.

Problems with oscillations near cutoff occurred in the above experiment. To stabilize the tube a continuous lossy wall was utilized which had a cold tube loss of 0.37 dB/cm at 35.0 GHz.[22] For higher overall gain the interaction length was increased to 43 cm. The tube was much more stable and produced a best observed small signal gain of 56 dB. The small signal 3 dB bandwidth at 1 amp beam current was 3.4% with a peak gain of 26 dB. The resistive wall loading of the gyro-TWT was found to suppress oscillations of both reflective and absolute instability types.

Studies of a modified gyro-TWT geometry which is predicted to increase the bandwidth to 12-50% are underway; the wideband modification involves tapering both the wall radius and the magnetic field strength along the axis of the interaction region.[25] Initial experimental results include a small signal 3 dB bandwidth of 12% with a 19 dB peak gain at midband (35 GHz).[26]

Experiments by Varian Associates near 5 GHz using the TE^0_{11} circularly polarized mode[17,18,27] have also produced impressive results. These experiments use a magnetron injection gun operating from 40 to 65 kV. The input coupling uses a sidewall junction to rectangular waveguide. The interaction circuit is 42.5 cm in length and has distributed wall loss over the first two thirds of its length for improved stability. Optimized performance was obtained by increasing magnetic field strength 4.4% from the input to the output end of the tube. With this ramped field, and with beam voltage and current at 65 kV and 7 A respectively, small signal gain was 26 dB at the center frequency of 5.18 GHz; saturated peak power was 120 kW at 26% efficiency with corresponding saturated gain of 20 dB and saturated bandwidth of 7.25% (FWHM).

The 5 GHz TE^0_{11} gyro-TWTs have also been extensively characterized as to other aspects of performance important in communications or radar systems. Measurements have been reported of AM and PM modulation coefficient, spectral purity, phase linearity, and noise figure.[18] Almost all of these parameters of the gyro TWT compared favorably with performance of present day coupled-cavity TWT's. The one parameter with a somewhat inferior value for gyro-TWTs was noise figure which was measured in the range 44-52 dB above thermal; improvement in this parameter may require the development of space charge limited electron guns which are compatible with good gyrotron operation.

There is good reason to be encouraged as to the eventual prospects for the practical use of gyro-TWTs in high-power, millimeter-wave communications and radar systems. Very high gain (56 dB) has been achieved in the 35 GHz amplifier, and bandwidths have been in the useful range of 1-12%. Power and efficiency have been lower than with the gyrotron oscillators but compare very favorably with conventional TWT's (viz., 120 kW with 26% efficiency at 5 GHz and 17 kW with 8% efficiency at 35 GHz) especially when one considers the preliminary state of the gyrotron amplifier work. Other characteristics of the gyro-TWTs which are important in signal processing appear to be of acceptable quality even in the preliminary devices and will surely be susceptible to improvement.

Gyromonotron Oscillators

It is projected that in thermonuclear reactors, highly efficient gyrotrons capable of multimegawatt power levels (cw) at frequencies of 100 GHz or greater will be required. This projection is driving exploration of new configurations and mechanisms so that the present state-of-art (Fig. 1) may be surpassed. As gyrotron circuits are designed for higher powers at shorter wavelengths, more attention must be paid to the conflicting problems of mode competition and thermal loading; design tradeoffs and operating limits are encountered. Thus, gyrotron oscillator research has many challenges still to overcome and is being actively pursued.

The gyrotron oscillator employs a cavity whose resonant frequency is close to Ω_c. As previously discussed, the gyrotron mechanism involves the interaction of a fast waveguide electromagnetic mode and the fast cyclotron wave on an electron beam. For a cavity oscillator, these two modes are respectively governed by two dispersion relationships similar to Eqs. (1) and (2) but with k_z set equal to $\pi l/L$ where L is the cavity length and l is the axial eigennumber.

The coupling between the two modes has been calculated by a number of authors.[15,28-32] The linear coupling yields the starting current for the oscillator. Chu[29] has calculated the starting current for a cavity in which the axial profile of the rf electric field is a half-sinusoid. Kreischer and Temkin[30] have used both sinusoidal and Gaussian profiles. The results differ significantly, with the Gaussian profile yielding substantially lower starting currents.

The calculation of nonlinear coupling leads to prediction of the efficiency of the oscillator. Various calculations have been made of the efficiency,[33-37] the most direct of which employ particle orbit integrating codes; rf field profiles of sinusoidal, Gaussian, and experimentally measured forms have been used in these calculations. The efficiencies predicted with the nonsinusoidal profiles are substantially above those given for the sinusoidal ones. High power gyrotrons generally use low Q cavities; these highly-output-coupled cavities have nonsinusoidal waveforms that can either be approximated by Gaussian profiles or, preferably, found by measurement of the fields excited in a cavity in the absence of the beam. Efficiency enhancement has been accomplished by profiling the cavity walls to obtain a more optimum field shape.[34,38,39]

Another method predicted to increase the efficiency is the profiling of the DC magnetic field.[33,40,41] Calculations with a linearly rising field[33] appear most useful and predict efficiencies to 78 percent. Efficiencies to approximately 65 percent are predicted with the cavity wall profiling.[35]

Enhancements of 20% to 90% in the efficiency have been observed[42] with moderate power ($P \leq 100$ kW) devices using magnetic fields which rise linearly toward the output end of the cavity. The results are summarized in Fig. 5. Interaction efficiencies (i.e., the efficiency of energy extraction from the beam into both the output wave and ohmic losses) of up to 65 percent were found in these experiments, in good agreement with theory. As in the case of cavity profiling, fairly long cavities were required for the highest efficiencies and high power devices may be limited to efficiencies of 50 to 60 percent.

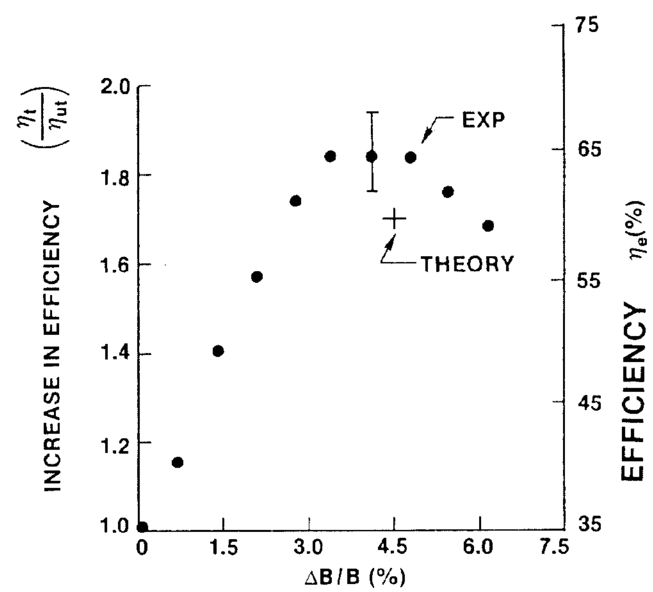

Fig. 5 — Increase in efficiency vs magnetic field taper for a 35 GHz gyromonotron oscillator ($L/r_w = 15$, $I = 15$ A, $V = 70$ kV). Figure adapted from Reference 42.

Since gyrotron cavities are overmoded, the degree to which they can be operated in a single, desired mode is of concern. This concern is of particular importance for cw devices with very high (≥ 1 MW) power at short wavelengths, where severely overmoded cavities are required.[43,44]

For a TE^0_{mn} mode, mode competition is predicted to some degree by the linear theory[30] for nearby modes with different radial, azimuthal, and axial eigennumbers. However, no competition due to modes of different axial mode numbers has been observed. (All reported devices operated in a $TE^0_{m,n,1}$ mode.) Recent nonlinear calculations support this observation.[45]

Competition due to modes with different azimuthal eigennumbers is predicted[43,44] and has been observed by Arfin and Read.[46] A $TE^0_{0,4,1}$ mode was desired in their experiment and was achieved for most values of magnetic field. However, for lower fields, the start current of the $TE^0_{2,4,1}$ mode was less than that of the desired mode, and the $TE^0_{2,4,1}$ mode was observed.

The linewidth of a gyromonotron at 35 GHz was measured to be less than 1 MHz, with the measurement apparently being limited by modulator voltage fluctuations.[11] More recent measurements indicate that the intrinsic linewidth of the gyrotron may be as small as 10 kHz.[47]

The modal purity of the radiation at the cavity output appears to be quite high. With the TE^0_{01} mode a measurement of >90% purity was reported.[11] For high power cw devices, where a large radius beam collector (which also serves as the output guide) is required, mode conversion in the transitions between the cavity, collector, and output window can be serious.[48]

One of the recent significant advancements in gyrotron development has been the realization of a 28 GHz gyrotron which yielded 212 kW on a continuous wave basis.[48] A carefully designed collector/output waveguide and a double-disk window with fluoro-carbon cooling was required for the cw operation. Devices with similar cw powers at 60 GHz are being designed.

From the foregoing, it is clear that the gyrotron oscillator is already highly developed. It has produced power at record levels, and seems destined to become a widely used device.

Agreement of theory and experiment is in general excellent. From the data base now existing it is possible to design devices with parameters over wide ranges. However, the gyrotron oscillator is hardly at the state where its potential has been completely realized. To close this section, we shall make a few comments as to the probable limits of operation of gyrotrons, and the areas of research which will be required for those limits to be reached.

For cw applications it appears that powers of 1-3 MW may be possible at frequencies on the order of 100 GHz. Results from the U.S.S.R.[8] have already demonstrated that this power and frequency goal is possible with a 100 μsec pulse duration. For a cw or long pulse device, it is likely that a TE^0_{0n} mode will have to be used, since ohmic losses with any other type of mode will be extremely high. (The megawatt tube developed in the U.S.S.R. used a mode with strong azimuthal variation ($\sim TE^0_{20,1,1}$). It may have been this aspect which limited it to short pulse operation.) Results of on-going studies at NRL indicate that a 1 MW (cw), 100 GHz device with a TE^0_{06} mode may be feasible.

For higher power cw operation or for higher frequencies, it may be desirable to utilize an alternate configuration termed a "quasi-optical gyrotron."[49,50] This device utilizes a Fabry-Perot type cavity; the electron beam propagation is perpendicular to the axis of the cavity. Calculations indicate that efficiencies similar to those achieved with the conventional "microwave cavity" gyrotron discussed above are possible, and the large volume quasi-optical cavity should have very low ohmic losses, allowing high average power. A proof of principle experiment for the quasi-optical gyrotron is currently being performed at NRL.

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