Overview of Advanced, Non-Klystron rf Sources

Steven H. Gold*
Beam Physics Branch, Plasma Physics Division, Naval Research Laboratory

A variety of sources are under development as alternatives to klystrons for powering future high-frequency colliders, or as test sources for developing high-gradient structures and high-power rf components. This paper discusses the two principal types of sources that are being developed, gyroklystrons and magnicons, and also considers two other devices, CARMs and gyroharmonic converters.

An important element of the program to develop colliders at higher center-of-mass energies has been the effort to increase the accelerating gradient in rf linear accelerators through the use of higher-frequency structures. The Stanford Linear Accelerator Center (SLAC) chose 11.424 GHz, four times the operating frequency of the Stanford Linear Collider, for their proposed Next Linear Collider, but the accelerator community has also considered collider operation using higher microwave frequencies, ranging from Ku-band (17 GHz) to Ka-band (30 or 34 GHz) to W-band (91 GHz) [1, 2]. At each frequency, a new high-power rf technology must be developed, starting with the required microwave source, a high peak power, high gain, high efficiency, moderate pulse length, narrow bandwidth, phase stable, low-duty-factor amplifier tube. SLAC has pursued 11.424-GHz klystron development for more than ten years [3], a program culminating in the present 50–75 MW PPM (periodic-permanent-magnet) klystron that is intended as a prototype tube for a future collider [4]. It, and a related series of klystrons employing solenoidal focusing, have been used to develop other required high power microwave technologies, including pulse compressors (the SLED2 and DLDS systems) and rf transmission line components, and have also been used to drive the Next Linear Collider Test Accelerator (NLCTA) in order to carry out high-gradient tests of linear accelerator structures.

In parallel with the klystron development, a variety of non-klystron sources have been under development for accelerator applications, many at frequencies above 11.424 GHz, to which conventional single-round-beam klystrons do not extrapolate favorably. Most of this work has been funded by the Advanced Technology R&D Program of the Department of Energy's Division of High Energy Physics, either directly through its "University Program," or indirectly through SBIR grants. While not precluding possible application to future colliders, many of these developmental tubes explicitly target parameters more appropriate for testing high-frequency rf structures and components. For this latter application, the strict requirements of an accelerator-class tube listed above can be relaxed somewhat, and moderate efficiency, moderate gain, moderate repetition rate, and perhaps only moderate phase stability will suffice.

The two rf sources that have received the most attention as high-frequency alternatives to the klystron are the gyroklystron and the magnicon. These two sources differ in very significant ways, but share the feature of a fast-wave output cavity operating at the cyclotron frequency, or, in the case of the gyroklystron, often at one of its low harmonics. Neither of these devices can use PPM focussing to replace the solenoidal magnet, since the physics of the interaction requires cyclotron resonance. Thus, in an accelerator context, both the gyroklystron and the magnicon would require the overhead of a superconducting magnet. However, the increasing development of "cryogen-free" superconducting magnets employing helium refrigerators, and the progress in high-temperature superconductors, may make this option more attractive in the future.

There are significant differences in the physics of high-power klystrons, gyroklystrons, and magnicons that affect how they extrapolate to high power at high frequencies. The two essential conditions for a microwave amplifier tube are a mechanism for the injected RF fields to bunch a DC electron beam into an AC electron beam, and synchronism between the bunched electrons and the RF fields in the output cavity, in order to coherently transfer energy from the electrons

*gold@ppdmail.nrl.navy.mil

into the rf fields. In the case of the multi-section output cavity of a high-power klystron, the interaction is a Cherenkov process that employs ballistic bunching [5]. The synchronism condition is $\omega - k_z v_z = 0$, where ω is the angular frequency of the radiation, k_z is the wavenumber of the radiation in the z direction, and v_z is the electron axial velocity. In any high-frequency device, it is impossible to decelerate a high-voltage (e.g., 500 keV) electron beam using rf fields in less than 1/2 wavelength in a single short cavity gap without exceeding rf breakdown fields on cavity surfaces. In the case of the klystron, the output cavity becomes a sequence of short coupled cavities forming a slow-wave structure. In addition, the cavity cross-section scales inversely with the frequency, leading to the usual slow-wave scaling law $P \propto f^{-2}$.

In the case of both the gyroklystron and the magnicon, the interaction is a bremsstrahlung process [5], and the resonance condition is $\omega - k_z v_z - s\Omega_c = 0$, where s is the cyclotron harmonic number and $\Omega_c/2\pi = 28\ \mathrm{GHz} \times B(\mathrm{T})/\gamma$, where γ is the usual relativistic factor. In this case, a "fast-wave" synchronism permits the use of a single long "fast-wave" output cavity, as well as the use of higher-order transverse modes of the output cavity. The use of larger structures provides higher power handling capability and easier fabrication. In these devices, the rf generation extracts principally the transverse momentum of the electrons, limiting the potential efficiency. In the case of the gyroklystron, this transverse momentum is created by acceleration across magnetic field lines in a magnetron injection gun (MIG) followed by adiabatic magnetic compression. The bunching involves a combination of ballistic bunching and the operation of the relativistic electron cyclotron maser instability.

In the case of the magnicon, the transverse momentum is produced by spinning up an initially linear electron beam in a series of deflection cavities containing synchronously rotating modes. In this case, an additional synchronism mechanism, the use of synchronously rotating modes in all of the deflection cavities as well as the output cavity, eliminates the need for a separate "bunching" mechanism, and makes the interaction invariant on the rf time scale. This increases the potential efficiency of the device.

The potential efficiency of high-power klystrons, gyroklystrons and magnicons is subject to certain limits. In the case of the klystron, space charge effects limit the axial bunching. As a result, the beam perveance can be related phenomenologically to the maximum efficiency. Symon's Law [6] has been found to predict the maximum efficiency of high-power klystrons: $\eta \leq 0.9 - 0.2k_\mu$, where k_μ is the microperveance of the electron beam. In the case of the gyroklystron, efficiency is the product of the transverse or bunching efficiency and the single-particle efficiency, which depends on the electron pitch ratio $\alpha = v_\perp/v_z$. Thus, $\eta = \eta_\perp \eta_{sp}$, where

$$\eta_\perp \leq 0.9$$

and

$$\eta_{sp} = \frac{\alpha^2}{1+\alpha^2}\frac{\gamma_0 + 1}{2\gamma_0} \leq 0.5$$

These formulas are derived for the case of constant axial magnetic field in the output cavity, and assume conservation of p_z, which is generally an excellent approximation in a gyroklystron, since it uses *TE* modes and $k_z \sim 0$. The maximum bunching efficiency observed in nonlinear simulations is approximately 0.9, while for $\gamma_0 = 2$ (500 kV) and $\alpha = 1.5$ (an estimated upper limit for a high-peak-power gyroklystron), the single-particle efficiency is 0.52. Thus the total efficiency η cannot easily exceed 0.45. In fact, this upper limit is not easily achieved in high-peak-power gyroklystrons because of constraints on the achievable beam α, which is often limited to values much less than 1.5 by problems in beam formation (velocity spread) and by the problem of spurious oscillations at various points in the gyroklystron as the beam α is increased.

For the magnicon, the output cavity once again has $k_z \sim 0$. However, the use of a TM mode in the output cavity makes it possible to decrease p_z, which oscillates every half rf period as an electron transits a multi-wavelength-long output cavity. In this case, p_z can end up at a lower value by careful choice of cavity length and other parameters. In addition, in all current magnicon designs, the axial magnetic field in the output cavity is not constant in the vicinity of the output cavity: it typically ramps upward from the penultimate deflection cavities through the output cavity, thus transforming p_z into $p_\perp$ during the interaction. Moreover, the proximity of the end of the last deflection cavity and the start of the output cavity makes it difficult to specify the precise value of α at the start of the output cavity interaction. By examining actual magnicon designs based on

particle simulations, it has been demonstrated that high power, harmonic magnicons can reach efficiencies greater than 60%. (The 7-GHz magnicon at the Budker INP demonstrated 55 MW at 56% efficiency [7].)

If one of the essential characteristics of an accelerator class tube is an efficiency greater than 50%, high-power klystrons and magnicons can achieve this directly, but the gyroklystron can only achieve this by postulating a depressed collector [8].

The major work on the development of accelerator-class gyroklystrons has been carried out at the University of Maryland by W. Lawson and coworkers. They have reported powers of approximately 30 MW at ~9.9 GHz and 19.8 GHz from a series of first and second harmonic gyroklystrons with typical efficiencies of ~ 30% [8]. (The maximum efficiency point of 37% in a first harmonic tube corresponded to approximately half of the maximum output power.) More recently, work began on coaxial gyroklystrons driven by a higher power 500-kV, ~ 500-A MIG. At 8.5 GHz, they have demonstrated 75 MW at 32% efficiency [9]. Work is now under way on a 17.1-GHz second-harmonic gyroklystron driven by this gun (which was recently rebuilt because of problems with cathode emission). The initial experiment produced ~28 MW. However, it was limited by azimuthally non-uniform emission from the electron gun and by the lack of flatness of the modulator voltage waveform. A new experiment using a rebuilt gun and a five-cavity circuit will begin in the near future. The long-range plan is to use this gyroklystron to test high-gradient accelerating structures at 17.1 GHz built by Haimson Research Corporation.

At 30 GHz, a gyroklystron design study is being carried out by M. Blank at Communications and Power Industries (CPI) under a contract from CERN. The present goal is a 50-MW design with a 1.2-μs pulse length, 100-Hz prf, and 80-dB total gain (gyroklystron+driver), from a coaxial circuit using a 500-keV, 300-A electron beam. The proposed application is to test CLIC rf structures and components.

At 91 GHz, Calabazas Creek Research (CCR) is developing a 10-MW gyroklystron under a DoE Phase II SBIR. The application of this tube is to test high-gradient W-band structures at SLAC.

The advantages of the gyroklystron include: 1) the best scaling to high power at high frequency; 2) well-understood device scaling; 3) accurate computer modeling; and 4) a substantial experimental track record. However, the challenges include: 1) the electron beam quality (limits beam α, limits efficiency); 2) stability throughout the device (beam tunnel, all drift spaces and cavities); 3) zero-drive stability of the operating mode; 4) stability of the output cavity in the presence of load mismatches; 5) isolation of the gain cavities in overmoded circuits; 6) controlling the quality factors and resonant frequencies of the gain cavities, while dissipating rf power in lossy materials; and 7) limited device efficiency, which would require the use of depressed collectors to exceed 45%.

Two experimental magnicon programs are under way in the US. The first, at 11.424 GHz, is being carried out at the Naval Research Laboratory (NRL) in collaboration with Omega-P, Inc. It is a frequency-doubling design that is designed to produce approximately 60 MW at 60% efficiency. This magnicon is undergoing high-power rf conditioning, and has already demonstrated 15 MW in a 1.2-μs FWHM pulse and 25 MW in a 200-ns pulse. Moreover, it has demonstrated a smooth drive curve and phase-stable output. The conditioning was interrupted for the temporary installation of an output window, which permitted the use of the output to test an active microwave pulse compressor [10] in collaboration with the Institute of Applied Physics (IAP). Those tests demonstrated that the magnicon could operate without problems into a resonant load (the pulse compressor cavity). Following the completion of the conditioning, the magnicon will be used for tests of dielectric-loaded accelerating structures [11], with the eventual aim of constructing a 20-MeV dielectric-loaded test accelerator, as well as for further tests of active pulse compressor configurations.

The second magnicon program, to develop a 34.272-GHz frequency-tripling amplifier, is being carried out at Omega-P, Inc. with DoE SBIR support. Its application would also be to the testing of high-gradient accelerating structures. It is still awaiting the arrival of key experimental components, but has carried out successful tests of an ultra-high convergence electron gun. The design parameters of the magnicon are 45 MW at 45% efficiency, using a 500-keV, 215-A electron beam with a radius of 0.8 to 1 mm. Its success would demonstrate high-power magnicon operation at a frequency and power level at which conventional single-beam klystrons are not likely to be feasible.

The advantages of the magnicon include: 1) high efficiency due to the synchronism between a well-focused spiraling beam and a rotating rf mode (time invariance); 2) the fast-wave output

cavity, which improves scaling to high frequency (compared to a klystron); 3) the reduction of mode competition due to the scanning-beam synchronism; 4) tolerance of resonant loads; 5) magnetic-field controlled beam loading, which provides simple control of deflection cavity Q values; 6) zero-drive stability; and 7) good phase stability. The challenges of scaling magnicons to high frequencies include: 1) the requirement for ultra-high compression ratio electron guns (2000–3000x) to produce the near-Brillouin beams required for high efficiency; 2) high rf fields in the penultimate $\lambda/2$ deflection cavities; 3) the use of a harmonic interaction in the output cavity increases the sensitivity to beam spreads. Also, as in any high-power device, the circuit design must pay careful attention to issues of stability and mode competition.

The cyclotron autoresonance maser (CARM) [12] is another gyroamplifier whose characteristics may lend themselves to high-power accelerator applications. In the CARM, the output frequency is significantly Dopper-upshifted from the cyclotron frequency. Potential advantages (compared to gyroklystrons) include: 1) high efficiency due to "autoresonant" compensation ($p_\perp$, p_z, and γ decrease simultaneously); 2) comparable efficiencies at lower values of α, which makes the device more stable against the excitation of parasitic modes (in a properly designed structure); 3) operation far from cutoff, which should reduce fields at cavity walls; and 4) operation at lower values of magnetic field. However, developing the CARM into a competitor to gyroklystrons for accelerator applications will involve solving some difficult challenges: 1) the difficulty in making mode-selective high-k_z cavities (quasioptical or Bragg reflector cavities required), 2) the requirement for a very low axial velocity spread (e.g., $\Delta p_z/p_z < 3\%$), moderate α ($\sim$1) beam, since the high-k_z interaction increases the sensitivity to axial velocity spread, 3) the stability of gyrotron and gyro-BWO modes (if waveguide cavities are used); and 4) the limited experimental track record, consisting mostly of short-pulse oscillators and traveling-wave amplifiers with efficiencies ranging from $\sim$5–25%. A new experimental program to explore the capabilities of a CARM driven by an advanced low-velocity-spread MIG could test the ability of CARMs to compete with gyroklystrons for future accelerator applications; however, no such program is currently under way.

The gyroharmonic converter [13] is another novel gyrodevice that may have application as a test source for accelerator development. It makes use of a fundamental-harmonic TE_{11}-mode cyclotron autoresonance accelerator for initial beam formation followed by a whispering-gallery mode TE_{m1} cyclotron resonance harmonic amplifier, where m is the harmonic number of the interaction. A number of experiments were carried out by J. Hirshfield and coworkers at Yale University and Omega-P, Inc. Several harmonics were achieved (3,4,5,7) in traveling-wave configuration, but serious competition with other harmonic and non-harmonic modes limited the experimental results. A new 7th harmonic, two-cavity version of this device is under development that is designed to produce 4 MW at 19.992 GHz, using 8.5 MW of drive power at 2.856 GHz. The electron beam is 20 A at 250 kV. The predicted efficiency from first-harmonic rf to 7th-harmonic rf is 47%, while the overall interaction efficiency is 30%.

In summary, substantial progress is being made in developing advanced, non-klystron rf sources for accelerator applications. It seems clear that the possible extrapolation of klystrons to higher frequencies will involve novel designs such as sheet beam and annular beam approaches to overcome the $P \propto f^{-2}$ scaling. The klystron competitors are all devices employing fast-wave interactions in the output cavity, which improves their extrapolation to high frequencies. The gyroklystron extrapolates best to high frequencies. However, gyroklystrons suffer from an inherent efficiency limit, and would require the use of depressed collectors to achieve efficiencies greater than 45%. In addition, they have not yet demonstrated certain other essential characteristics, such as the ability to drive resonant loads. The magnicon can have efficiencies comparable to high-power klystrons, and has already demonstrated the ability to drive resonant loads. However, it is more difficult to extrapolate the magnicon to high frequencies because of the use of $\lambda/2$ deflection cavities; this is one of the reasons that high-power magnicons have been built in frequency-multiplying configurations. The 34-GHz frequency-tripling device being built at Omega-P, Inc. is exploring this frequency limit. The rate of progress for these advanced sources has been constrained by the limited resources available, compared to those in the klystron development program at SLAC. Nevertheless, the next few years should produce new results from a variety of promising accelerator-class amplifier experiments, as well as tests of a number of these sources to drive accelerator structures or other accelerator-relevant loads. However, it is worth noting that the final competition for future colliders at frequencies above X-band will most likely be between colliders using discrete rf sources and two-beam accelerator concepts. In this context, it is useful to point out that even two-beam accelerator development will require discrete

sources for high-frequency component development and testing.

Acknowledgments

I am grateful to G. Nusinovich, B. Danly, M. Blank, A. Fliflet, J. Hirshfield, L. Ives, W. Lawson, and O. Nezhevenko for sharing their recent research results and for useful discussions. This work was supported by the Department of Energy and the Office of Naval Research.

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