GYROTRON INTRODUCTION FOR ECRIS 2008

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Abstract

Gyrotrons are proving to be very reliable sources of high power at frequencies in the range of 28 to 170 GHz, where other sources are very limited in power capability. As a specific example for ECRIS applications, a 10 kW, 28 GHz CW gyrotron has made possible significant increases in the ion currents generated by the Venus ion source at the Lawrence Berkeley Laboratory [1]. In this paper we briefly discuss the physics and engineering aspects of the gyrotron oscillator, point out some of the issues that require special treatment in the control system and power supplies for it, review related gyro-devices, and present important applications.

INTRODUCTION

The history of gyrotrons goes back to the 1950s. The basic idea of a cyclotron resonance interaction was recognized by a number of people. Particular recognition should be given to Russian scientists under the leadership of A. V. Gaponov [2]. A more recent detailed review of gyro-devices is given in [3].

Figure 1 shows specific CPI gyrotrons and other selected gyrotron sources in a plot of average power output versus wavelength. They occupy an empty region between lasers and conventional vacuum electron devices (VEDs) like klystrons, traveling-wave tubes, and magnetrons. The domain of solid-state devices is similar to conventional VEDs but at lower power level. A more detailed listing of gyrotrons worldwide can be found in [4].

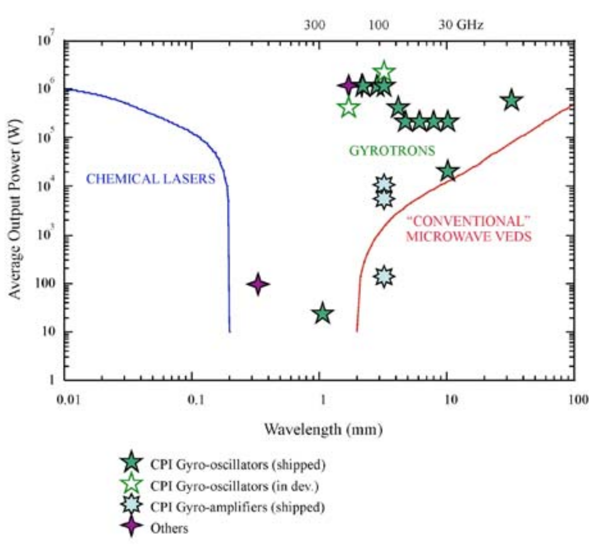

Figure 1: The role of gyrotrons in frequency-power parameter space

BASICS OF THE GYROTRON INTERACTION

Gyrotrons make use of the strong coupling that takes place between an electron moving in a circular orbit perpendicular to a dc magnetic field and an electromagnetic field in the plane of the orbit which has a frequency near the cyclotron resonance frequency of the electron.

The left side of Figure 2 shows 8 electrons at some initial time distributed equally around the orbit center. The electron in position 7 sees a maximum decelerating force, and the one at 3 sees maximum accelerating force. One half cycle later the field has reversed polarity and 7 has moved half way around the orbit and again is decelerated. Likewise 3 is again accelerated. At 1/4 and 3/4 cycle times the electric field is zero and only magnetic forces exist.

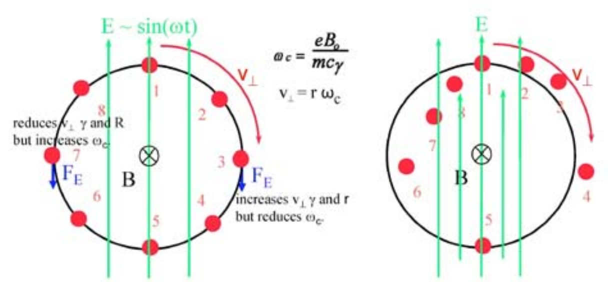

Figure 2: Electrons at cyclotron resonance with a time-varying electric field

The right side of Figure 2 shows the situation an integral number of cycles later, when the cumulative forces have produced a bunching in the rotational phases of the electrons. In this case there is no net energy loss of the electrons because equal numbers have been accelerated and decelerated. If, however, we have a slight difference between ω and ω_c, we can arrange for the bunch to form in a region of decelerating force, and the loss of electron energy will cause the electric field to grow.

To create a gyrotron we introduce a microwave resonator to define a volume for the fields and create an electron beam where all electrons have the same transverse component of velocity, $v_\perp$, and a small component of axial velocity so that the electrons are removed from the cavity before they slip further into a phase to gain energy back.

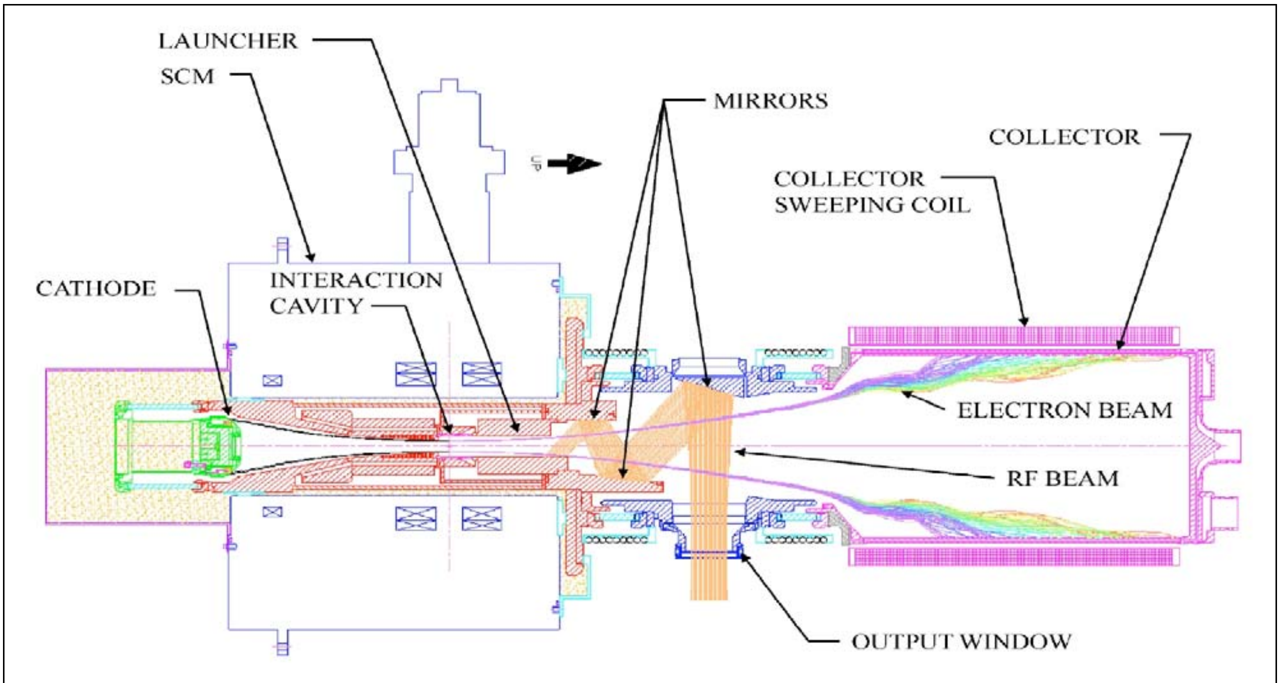

Figure 3: Layout of a 95 GHz, 2.5 MW gyrotron

Figure 3 shows the basic layout for a multi-megawatt gyrotron at 95 GHz. The required magnetic field is created by a superconducting magnet (SCM), which has two main coils to supply the field close to cyclotron resonance at the cavity, and a third coil near the cathode to help control the transverse energy of the electrons. The 95 GHz interaction cavity uses the $TE_{22,6,1}$ mode, and is formed by a slight diameter step on the left side and a slight up taper on the right. (Choice of operating mode is frequency and power dependent.)

The desired electron beam for interaction in the cavity is a thin hollow cylindrical beam having a ratio of transverse-to-axial velocity typically in the range of 1.3 to 2. For efficient operation, all electrons should have the same velocity components. At the cathode, the magnetic field is mainly axial and the electric field has both radial and axial components to launch the beam with a specific amount of transverse velocity. Space-charge forces are minimized to achieve good beam quality by operating the cathode in a regime where cathode temperature controls the amount of current emitted. In traveling from the cathode to the cavity the axial magnetic field amplitude increases to bring the transverse-to-axial velocity ratio to the desired value by adiabatic compression.

In the interaction cavity, the electrons lose 30 to 50% of their total energy, mostly by reduction of transverse velocity due to interaction with the transverse electric field of the resonant cavity mode. The cavity and beam parameters are chosen so that the electrons exit the high-field region of the cavity before they become re-accelerated by the resultant cavity fields.

The millimeter-wave power generated by the interaction passes out the right side of the cavity as a circularly polarized $TE_{22,6}$ mode. The launcher waveguide uses a pattern of small perturbations on its inner surface to convert the operating mode into a quasi-Gaussian mode, which is further shaped and optimized by the three mirrors.

The final mirror sends the beam through the output window. For very high power gyrotrons, a CVD diamond disc is used for the window. This material has the low dielectric loss, high strength, and high thermal conductivity properties that are needed to handle such high power at this frequency.

As the spent electron beam leaves the interaction cavity it enters a region where the dc axial magnetic field decreases in amplitude. This causes adiabatic reduction in the remaining transverse velocity with a corresponding increase in the axial velocity, average radius of the beam, and orbit radius of the electrons. This process reduces the power density of the beam to a point where it can be collected on a water-cooled copper collector.

For lower power gyrotrons, lower order cavity modes and smaller collectors can be used. If the collector power density is small enough, a launcher and mirrors are not required, since the collector can serve as an axially directed waveguide with an output window at the end.

ALTERNATIVE GYROTRON CONFIGURATIONS

The gyrotron oscillator described above is basically a single frequency device. It can be tuned slightly over a frequency range of the order of 1/Q, where Q is the loaded Q of the interaction cavity, typically in the range of 500 to 2000. This slight tuning is best accomplished by increasing the dc magnetic field beyond the optimum value. The power output will drop approximately linearly to zero as the frequency is tuned.

Alternative gyro-device configurations are shown in Figure 4. On the left is a two-cavity gyro-klystron amplifier. An input signal is coupled into the first cavity through holes in the sidewall. The first cavity is only long enough to allow azimuthal bunching of the electron beam to begin. In the space between the two cavities, the drifting allows the bunching to become tighter. The second cavity is long enough to extract maximum energy from the beam. The gain and the bandwidth of the amplifier can be increased somewhat by adding additional cavities between the input and output cavities. A typical practical bandwith is 1 %.

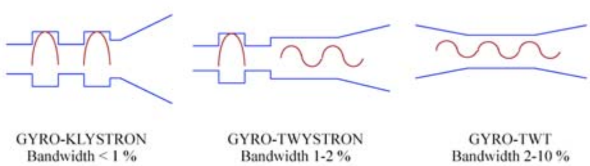

Figure 4: Alternative gyrotron configurations

The configuration on the right is a gyro-TWT (gyro-traveling-wave tube), where the interaction circuit is a waveguide rather than a cavity. For strong interaction the frequency must be close to the cutoff frequency of the mode of interest. Practical bandwidths are in the range of 2-10 %. A useful gyro-TWT must be stabilized by adding waveguide attenuation or loss to avoid oscillation with a waveguide mode traveling in the backward direction.

Another configuration called a gyro-twystron is shown in the center. It has a typical bandwith of 1-2 % by using a cavity for the input and a waveguide for the output. All of these amplifier configurations require a microwave input at a power level typically 30 or 40 db below the output power level.

Another variation (not shown) is called a gyro-BWO (gyro-backward wave oscillator). It uses the interaction that was avoided by introducing loss in the gyro-TWT. It can produce an output that can be tuned in frequency by changing beam voltage. Practical problems are that the output propagates to the left, opposite to the beam, and the efficiency is not as high as with the other configurations. It can produce an output over a 10-20 % frequency range.

GYROTRON POWER SUPPLY AND CONTROL ISSUES

Gyrotrons have power supply and control requirements similar to other microwave vacuum devices, with a few exceptions.

The temperature-limited cathode current has important implications for operating a gyrotron. Rapid changes in beam current are not possible because the thermal time constant for changing cathode temperature is of the order of 30 sec to 1 min.

Rapid changes in the gyrotron output power can be realized by rapid changes in beam voltage. The change in beam voltage directly changes the transverse energy of the electrons.

The axial magnetic field amplitude and axial profile are much more critical for the gyrotron than for linear beam microwave devices. For good performance the magnet current must typically be controlled to one part in 5000. A control system for the 28 GHz, 10 kW gyrotron is described in more detail in [5].

GYROTRON APPLICATIONS

A major application of gyrotrons has been for electron cyclotron resonance heating (ECRH) in fusion energy research. ECRH is one of the predominant methods for heating magnetically confined fusion plasmas. Frequencies have ranged from 28 to 170 GHz, with present state-of-the-art gyrotrons producing continuous wave (CW) power levels up to about 1 MW.

Industrial and scientific applications have included ceramic sintering, ion sources based on ECR, and surface treatment.

Figure 5 shows a 1 MW CW, 110 GHz, CPI gyrotron,

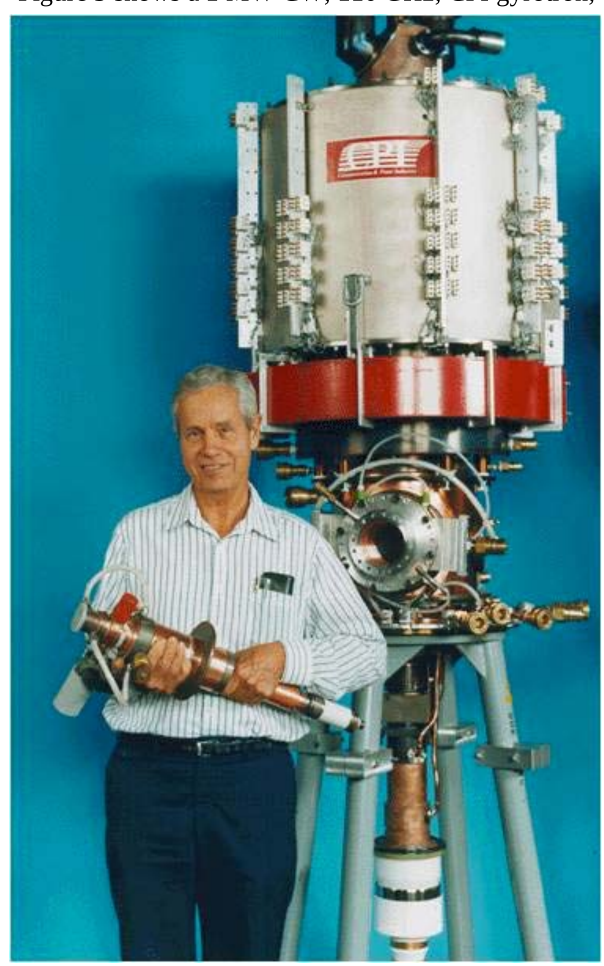

Figure 5: A 1 MW gyrotron and a 10 kW gyrotron

developed for the US Department of Energy for use at the DIII-D Tokamak at General Atomics. A total of six gyrotrons have operated simultaneously to heat the plasma in that system. This gyrotron operates in a superconducting magnet, which is not shown in the picture.

The smaller gyrotron in Figure 5 is a CPI 10 kW CW, 28 GHz gyrotron used in the Venus ion source and other industrial applications. It operates in a room temperature copper magnet (not shown) that requires 5.5 kW of power. In this case, the electron beam interacts with a mode at the second harmonic of the cyclotron frequency, so the required magnetic field is halved, and electrical power required for the magnet is greatly reduced.

Gyro-TWTs and gyro-klystrons have been delivered for use in radar systems. Figure 6 shows a 95 GHz gyro-twystron with a 1.5 GHz bandwidth, installed in its superconducting magnet for electrical testing. The magnet uses a closed-cycle helium refrigerator so the regular addition of liquid helium is not required. The cold head is shown at the bottom left of the picture. Three magnet coils are shown above the main magnet to control the spent beam distribution in the collector.

Another interesting application shown in Figure 7 is the Active Denial System (ADS). This is a military system

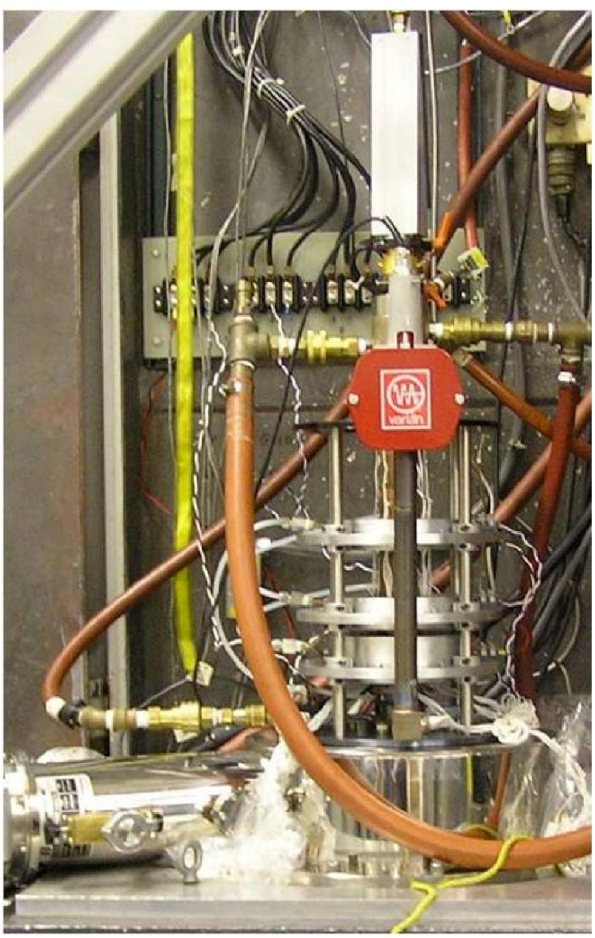

Figure 6: A 95 GHz gyro-twystron installed for testing

being tested for use in dispersing hostile groups of people as an alternative to using lethal force. It uses a CPI 95 GHz, 100 kW gyrotron. At 95 GHz the depth of skin penetration is less than 1/64th of an inch, causing a very uncomfortable heating sensation without producing permanent damage.

Figure 7: ADS system using a 100 kW, 95 GHz gyrotron

CONCLUSIONS

Gyrotrons have proven to be very useful to supply high power in a part of the electromagnetic spectrum where it has not been available from other sources. A number of interesting applications are emerging as a result.

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