The Russian lead in radio frequency weapons

One reason Gorbachov doesn't mind banning nuclear missiles from Europe, is that he's got something better. Robert Gallagher reports on Russian breakthroughs in RF as an anti-personnel weapon.

Russian negotiators at the Strategic Arms Limitation Talks (SALT II) in the late 1970s proposed a ban on "a new generation of weapons of mass destruction" that use "pulses of intense electromagnetic radiation" against equipment and personnel, according to reports in aerospace and arms-control publications, now confirmed by sources close to the Pentagon. The Russians were probing for information on the state of development of U.S. technology in the area. The proposal reportedly was tabled because U.S. negotiators did not then understand what the Russians were talking about.

Now, almost a decade later, publicly available information on Russian development of compact sources of electromagnetic radiation at radio frequencies, delivered in pulses of millions to billions of watts in billionths of a second, combined with Russian scientists' early pioneering work on the effects of such short pulses of coherent electromagnetic radiation on chemical and biological processes, present the horrifying picture that they have developed and are close to deploying offensive weapons superior to the nuclear missile, which the Russian-controlled Pugwash Conferences in the West had proclaimed "the ultimate weapon." The new weapons will have the capability of disabling or destroying NATO military installations, weapons systems, and troops without the destructive effects to Western European industry and real estate that the Russians would like to prevent during a war in Europe, but which nuclear weapons would destroy while rendering whole areas radioactive and uninhabitable.

The new weapons are one reason why Russian party secretary Mikhail Gorbachov is agreeable to banning the nuclear missile from Europe. "No nukes, no mess," he reasons. "Just dead Western Europeans and Americans."

The fact that high peak power, short-pulsed microwave devices can destroy the electronics of aircraft, tanks, or missiles, is publicly acknowledged. Lawrence Livermore National Laboratory is investigating the destructive effects of microwaves on military electronics. The March 1987 issue of the lab's *Energy and Technology Review* writes of "microwaves weapons" and "the threat of offensive electromagnetic energy":

> A high-intensity burst of electromagnetic energy can pose a threat to military systems, such as aircraft and satellites. The source of the high-intensity, high-frequency pulse can be either a nuclear detonation or a microwave-generating weapon. The nuclear detonation would broadcast a single, omnidirectional burst of electromagnetic energy (a monopulse), whereas the microwave weapon would focus and aim a train of microwave-carrier pulses. In either case, the threat derives from the possibility that damaging amounts of the energy would find their way to the inner workings of a system's susceptible electronic devices. The possible effects range from confusion of electronic-system function to destruction of sensitive electronic components. These adverse effects could result even if only part of the energy should penetrate the outer covering of a system.

Of more serious consequence are electromagnetic antipersonnel weapons. The principles upon which they may function are not well understood in the West. What we present here are the results of a preliminary *EIR* study based on known effects of the interaction of coherent radiation with matter.

Gigawatt radio frequency devices

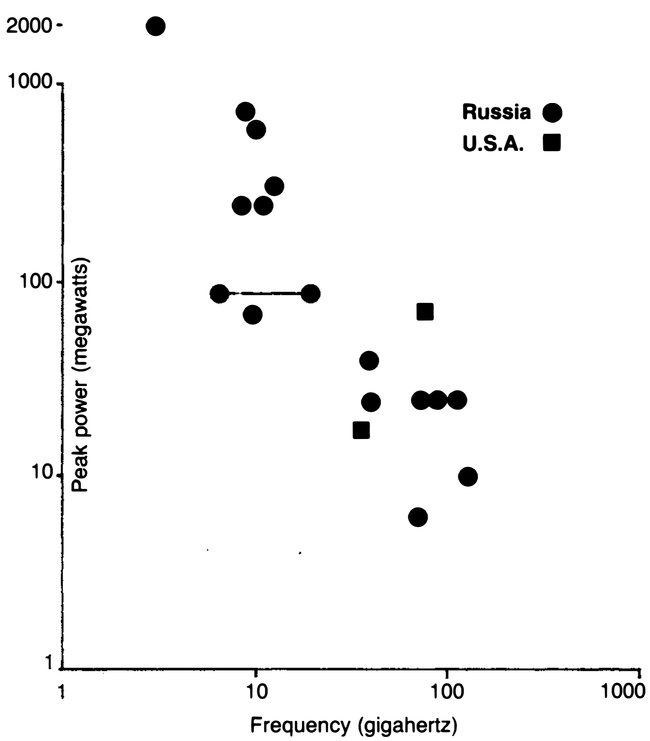
In 1975, a team of physicists led by M.S. Rabinovich and A.A. Rukhadze at the Lebedev Physics Institute in Moscow announced that they had produced from a cyclotron resonance maser, microwave pulses of electromagnetic radiation 35 billionths of a second long (nanoseconds) with a radio frequency of 10 billion cycles per second (gigahertz) and a pulse peak power of 2 million watts (megawatts). The following year, another Russian team led by A.N. Didenko at the Nuclear Physics Institute in Tomsk, reported generation of 3-gigahertz, 50-nanosecond microwave pulses with a peak power of 1,000 to 2,000 megawatts from a type of cyclotron resonance maser called a "gyrotron," which generates electromagnetic radiation from an electron beam gyrating in a helix. The device operated at an efficiency of 30%. In 1978, the Lebedev group announced generation of pulses of 60 megawatts power at 15% efficiency from a plasma-filled gyrotron operating at the same frequency and pulse length as their 1975 device. In subsequent years, Russian research groups at Lebedev and at the Institute for Applied Physics in Gor'kiy, reported routinely producing nanosecond pulses of tens of megawatts of cyclotron resonance maser microwave output power at higher and higher frequencies up to 125 gigahertz, until much of the work was classified (**Figure 1** and **Table 1**).

The highest peak power ever achieved in pulsed gyrotron operation in the United States is 645 thousand watts (kilowatts) at 141 gigahertz. This result, just announced June 1 by the Massachusetts Institute of Technology Plasma Fusion Center at the 1987 Institute of Electrical and Electronics Engineers (IEEE) Conference on Plasma Science, is only 1/15th of the power reported achieved in 1982 by V. Bratman of the Institute of Applied Physics at Gor'kiy, from a cyclotron resonance maser operating at the roughly comparable frequency of 125 gigahertz. The MIT device produces pulses 3,000 nanoseconds long and is more appropriate for heating thermonuclear plasmas than for the weapons applications that the Soviets appear to have oriented most of their gyrotron program toward.

Otherwise, typical U.S. gyrotron peak powers elsewhere in the microwave spectrum are 150 to 300 kilowatts. From the standpoint of short, high peak power pulses, the Soviet gyrotron program is "out of sight."

FIGURE 1

Russia leads U.S. in mobile, short-pulse, high peak power gyrotrons



Russia has developed efficient, mobile radio frequency devices that produce high peak power from 3 to 125 Gigahertz. The two U.S. points on the graph are results of experiments with low-efficiency but apparently compact free electron lasers.

Intense multiple-photon action

Devices that produce high peak power, tens-of-nanoseconds (or shorter) pulses of electromagnetic radiation, have the potential to serve as either anti-personnel weapons, or the basis for new breakthroughs in medicine. The action on living tissue is not simple heating, but is nonlinear.

Radio frequency pulses have the potential to penetrate living tissue. Once inside, an intense, highly coherent pulse of microwaves (for example) can have the effect of higher frequency coherent infrared, visible, or ultraviolet light (or even coherent x-rays or gamma rays) through a nonlinear process well established within laser chemistry, called "multiple photon excitation." In one example of multiple photon excitation, the photon disassociation of a molecule which ordinarily requires absorption of radiation within a specific band or range of frequencies (or wavelengths), is accomplished with coherent radiation of a lower frequency if a short, high power pulse with sufficient coherence is used. It is thought that two or more lower frequency photons (units of coherent radiation) act together to effect a transformation requiring high frequency photons. **Figure 2b** reproduced from *Los Alamos Science*, illustrates the multiple photon action of intense coherent radiation. In the hypothetical case shown there, a pulse of infrared radiation excites a molecule through over 40 quantum transitions, though the wavelength of its radiation is only resonant with two or three of them.

There are a host of multiple photon processes, and new ones are being discovered regularly. In another example, radiation of two different wavelengths, neither of which is resonant with the quantum transitions of a molecule, somehow act together to excite a molecule through two or more transitions to dissociation, for example. These effects have already made industrial laser chemistry considerably more feasible.

Multiple photon processes are well established in the international scientific literature. Los Alamos National Laboratory's Molecular Laser Isotope Separation process in part used nonlinear multi-photon excitation of uranium isotopes with infrared radiation. Recently, a patent was granted to the Amoco Corporation for a multi-photon process to dissociate hydrogen bromide to produce a chemical chain reaction for production of ethyl bromide from ethylene (see *EIR*, June 26, 1987). Given that radio frequency electromagnetic radiation (which ranges from Extremely Low Frequencies to hundreds of gigahertz), can penetrate living tissues, through nonlinear multi-photon action it may provide a vehicle for combatting diseases like cancer or AIDS.

The systematic investigation of nonlinear radio frequency multiple photon spectroscopy of organic material and living tissue, must now become a national research priority at least as large as it is in Russia. The requirements in pulse length, peak power, and coherence of the radiation source must also be examined. Since it is usually easier to break something than fix it, the weapons applications of multiple photon radio frequency biophysics, to destroy life processes, have come first.

In the development of the nonlinear multiple photon chemistry and physics of coherent radiation, it is the Russian biologists, such as Vladilen S. Letokhov of the Institute of Spectroscopy at the Russian Academy of Science, who have led the way. The Rand Corporation reports that Russian investigators began using high peak power short pulse gyrotron

TABLE 1

Only the Russians have systematically developed transportable, high peak power, short pulse gyrotrons

Frequency (GHz)	Wavelength (mm)	Peak Power (MW)	Pulse Length[1] (nsec)	Electronic Efficiency (%)	Date Reported	Principal Investigator	Lab[2]	Notes
3	100	2,000	50	30	1976	A. Didenko	Tomsk	
12.5	24	300	80*	15	1982	N. Zaytsev	Gor'kiy	
40	7.5	23	20	6	1982	V. Krementsov	Lebedev	Terek-2 accelerator
40	7.5	40	20	10	1983	P. Strelkov	Lebedev	Terek-2
70	4.3	6	5-30	4	1982	M. Petelin	Gor'kiy	CARM with Bragg mirrors
79	3.8	20-30	100*	3	1984	V. Bratman	Gor'kiy	Neptun-2; Q=400
88	3.4	20-30	100*	1	1984	V. Bratman	Gor'kiy	Neptun-2; Q=100
107	2.8	20-30	100*	1	1984	V. Bratman	Gor'kiy	Neptun-2; Q=100
125	2.4	10	20-30	2	1982	V. Bratman	Gor'kiy	CARM with Bragg mirrors; Neptun-2 accelerator
Plasma-filled Devices								
2.6	115	10	30*	0.02	1972	Y. Tkach	Khar'kov	Plasma Cherenkov device
9.1	33	200-300	30*	NA	1979	Y. Tkach	Krar'kov	with vacuum
9.1	33	700	30*	22	1979	Y. Tkach	Krar'kov	with plasma
10	30	200-300	15-20	2	1975	Y. Tkach	Krar'kov	Slow-wave device:vacuum
10	30	600	15-20	2.7	1975	Y. Tkach	Krar'kov	Slow-wave device:plasma
10	30	2	35*	0.4	1975	V. Krementsov	Lebedev	Terek-2; plasma
10	30	60	30*	15	1978	A. Rukhadze	Lebedev	Terek-2; plasma
10	30	25	35*	20	1978	V. Krementsov	Lebedev	Terek-2; with vacuum
10	30	65-70	35*	20	1978	V. Krementsov	Lebedev	Terek-2; with plasma
6.5-20	15-46	90	45*	21	1982	P. Strelkov	Lebedev	Terek-2; plasma

[1] "Pulse length" refers to output microwave pulse length except when marked with an asterisk; there electron beam pulse length is given. Output pulse can be varied up to about 90-95% of electron beam pulse length.

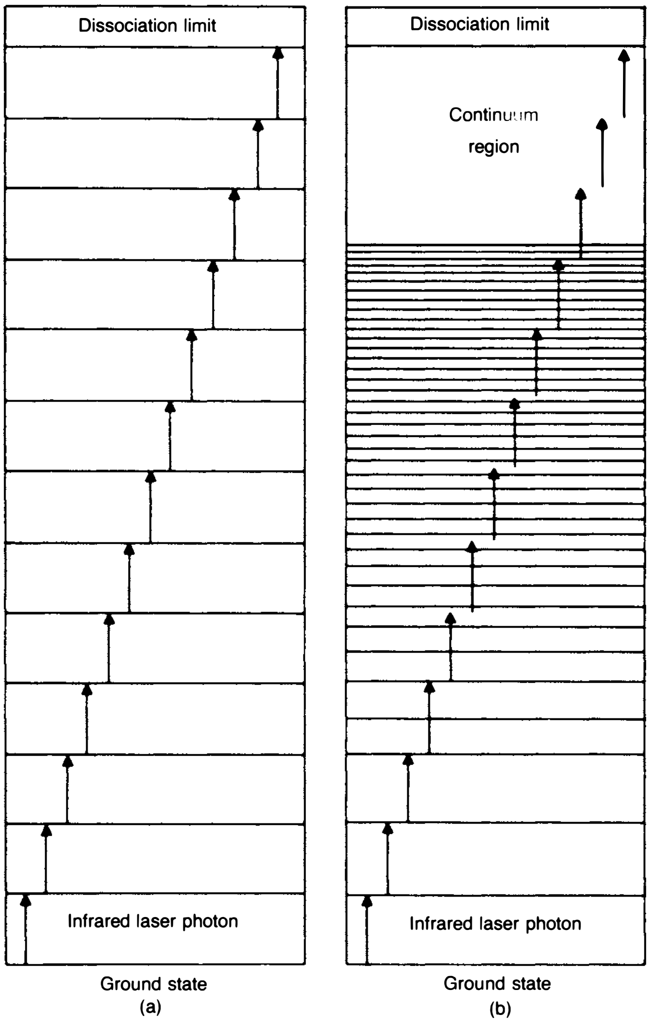
[2] "Gor'kiy" refers to the Radiophysics Institute at Gor'kiy which was transferred in 1977 to the new Institute of Applied Physics there. "Lebedev" refers to the Lebedev Physics Institute in Moscow. "Khar'kov" refers to the Khar'kov Physico-Technical Institute. "Tomsk" refers to the Nuclear Physics Institute in Tomsk.

Sources: S. Kassel, "Soviet Development of Gyrotrons," Rand Corp. Report R-3377-ARPA, May 1986; V.L. Granatstein, "High Average Power and High Peak Power Gyrotrons," *Int. J. Electronics*, 1984, vol. 57, no. 6.

Legend: GHz = Gigahertz; mm = millimeters; MW = megawatts; nsec = nanoseconds; CARM = cyclotron autoresonance maser, a type of free electron laser. A Cherenkov device is also a type of free electron laser.

microwave oscillators in the early 1970s for "high resolution spectroscopy and to investigation nonlinear self-focusing of intense electromagnetic waves in plasma." High resolution spectroscopy is the first step in mastering the action of coherent radiation on biological material.

FIGURE 2
The multiple photon effect



In multiple-photon excitation a molecule absorbs many infrared photons of the same energy. If the molecule's vibrational energy levels were equally spaced as in (a), multiple-photon excitation could be understood as a resonant excitation at each step of the vibrational ladder. The absorbed photons are represented by arrows whose lengths exactly match the constant energy spacing between levels in (a). But, as shown in (b), the vibrational ladder for any physical molecule is anharmonic. That is, the spacing between vibrational levels decreases with vibrational energy. Therefore, the energy of the absorbed photons becomes increasingly mismatched with the energy spacing.

Source: *Los Alamos Science*, Winter/Spring 1982, p. 13.

The Russian program to develop high peak power radio frequency devices has involved scientists active in its strategic defense program: Leonid Rudakov of the Kurchatov Atomic Energy Institute (who specializes in intense relativistic electron beams), A.A. Rukhadze and Y.A. Vinogradov of the Lebedev Physics Institute (who specialize in plasma electronics and x-ray lasers), and many others.

A useful review of Russian work on radio frequency devices is Rand Corporation Report R-3377, "Soviet Development of Gyrotrons," by Simon Kassel (May 1986). Soviet, European, and American results with gyrotrons are published in English in special issues of the *International Journal of Electronics*. Several Russian journals that report on the area are available in English translation: *Soviet Radiophysics and Quantum Electronics, Soviet Radioengineering and Electronic Physics,* and *Soviet Radio Electronics and Communication Systems.*

How did it happen that the Russians developed high peak power gyrotrons that at some frequencies operate efficiently at peak powers three orders of magnitude greater than any in the West?

Both the United States and Russia have programs to develop high average power long-pulse or continuously operating gyrotrons for plasma heating in magnetic plasma confinement machines like the Tokamak. In this area of high average power devices, the United States is not as far behind the Russians. Russian scientists had developed megawatt power, long pulse gyrotrons by 1978. One U.S. research lab has recently achieved long-pulse gyrotrons producing six-tenths of a megawatt.

There is a peculiar asymmetry to the Russian work on high average power gyrotrons (**Table 2**). This work has almost entirely been conducted at the Institute of Applied Physics in Gor'kiy (which incorporated the Radiophysics Institute in 1977). It was intense there after A.P. Gaponov and M.I. Petelin built the world's first gyrotron in the mid-1960s, but slacked off considerably after the mid-1970s achievements in high peak power gyrotrons at Tomsk and Lebedev. Then, in the 1980s, personnel at Gor'kiy began to publish results on work new to the lab, generation of high peak power pulses from gyrotrons and other cyclotron resonance masers. Petelin and V. Bratman led research teams in virtual competition with those at Lebedev. The work on high average power devices became more and more devoted to raising the frequencies and the harmonics at which gyrotrons would efficiently produce radiation.

Since the 1960s, Soviet personnel involved in gyrotron research has increased six-fold (**Table 3**). However, as the number of personnel involved in the program has risen, the number of scientific papers reporting on results in the open literature available to the West, has declined. The Rand report concludes:

> The significance of the published material on Soviet CRM and gyrotron research also resides in what

it should be expected to, but does not, say. There are many indications that a substantial portion of this research has been classified over the years. A general impression that this is the case is obtained from the publication pattern of the research reports in this area, showing a discrepancy between the annual publication frequencies and the number of research personnel accounted for in each year. The former shows a peak in the mid-1970s followed by a sharp drop, while the latter, as noted above, has been rising during the same

TABLE 2

The Russians also lead the U.S. in development of high average power gyrotrons

Frequency (GHz)	Wavelength (mm)	Peak Power (kW)	Pulse Length[1] (microsec)	Electronic Efficiency (%)	Date Reported	Principal Investigator	Notes
Russian Devices[1]							
15	20	3	cw	50	1966	A. Gaponov	
15	20	380	3	45	1972	A. Gol'denberg	
25	12	4.3	cw	18	1966	A. Gaponov	
33	9	140	cw	25	1984	V. Flyagin	2nd harmonic
34	8.9	10	cw	40	1974	Sh. Tsimring	2nd harmonic
34	8.9	30	5	43	1974	Sh. Tsimring	2nd harmonic; 400 pulses per sec
34	8.9	120	pulsed	23	1977	Sh. Tsimring	2nd harmonic
45	6.7	1,250	pulsed	35	1978	M. Petelin	
54	5.6	150	cw	10	1984	V. Flyagin	3rd harmonic
60	5	10	500	NA	1974	N. Koralev	50 pulses per sec
75	4	156	100	34.6	1984	G. Nusinovich	for plasma diagnostics
75	4	212	100	19	1984	G. Nusinovich	for plasma diagnostics
83	3.6	200	150,000	NA	1983	V. Alikayev	Tokomak T-10 ECRH; operational
94	3.2	300	100	25	1984	G. Nusinovich	for plasma diagnostics
100	3	1,100	pulsed	34	1978	M. Petelin	
108	2.78	12	cw	31	1973	N. Zaytsev	
150	2	22	cw	22	1978	M. Petelin	
157	1.91	2.4	cw	9.5	1973	N. Zaytsev	
157	1.91	7	pulsed	15	1974	N. Zaytsev	
136-250	1.2-2.2	10-20	3.5	10	1974	M. Ofitserov	
250	1.2	4.3	cw	18	1975	A. Gaponov	
326	0.92	1.5	cw	6.2	1973	N. Zaytsev	2nd harmonic
375	0.8	120	80	15	1982	G. Nusinovich	for plasma diagnostics
423	0.71	80	80	15	1982	G. Nusinovich	for plasma diagnostics
500	0.6	100	80	8.2	1982	G. Nusinovich	for plasma diagnostics
Best U.S. Devices							
28	10.7	212	cw	45	1980	Varian	
28	10.7	250	40,000	45	1980	Varian	
35	8.6	150	20,000	31	1980	NRL	
35	8.6	340	1	50	1983	U. Md.	
60	5	214	cw	33	1983	Varian	
115	2.6	53	1.5	30	1984	NRL	
141	2.1	645	3	24	1987	MIT	step-tunable from 119 to 148 GHz

[1] With the exception of the operational use of an 83 GHz gyrotron for electron cyclotron resonance heating (ECRH) on the Tokamak T-10 at the Kurchatov Atomic Energy Institute, all Russian work reported here was carried out at the Radiophysics Institute of the Institute of Applied Physics at Gor'kiy.

Sources: See Table 1, plus: R. Temkin, "Recent advances in gyrotrons and FELs," IEEE Microwave Society Meeting, June 1987; A. Fix, et al., "The problems of increase in power, efficiency and frequency of gyrotrons for plasma investigations," *Int. J. Electronics*, 1984, vol. 57, no. 6; V. Granatstein et al., "Measured performance of gyrotron oscillators and amplifiers," *Infrared and Millimeter Waves*, vol. 5, 1982, Academic Press.

Legend: see Table 1, plus: kW = kilowatts; cw = continuous wave output; Varian = Varian Associates; NRL = Naval Research Lab; U. Md. = University of Maryland; MIT = Massachusetts Institute of Technology.

period. Assuming that individual productivity averaged over the group and over time is constant, the discrepancy leaves a substantial body of papers missing from the publications after 1975 which could be attributed to classification.

The entrance of the Lebedev Institute into the gyrotron development program in the mid-1970s indicated that a major national effort was underway.

A typical Soviet applied research program is confined to a single institute, while most of the time only programs of major national importance are supported by a coordinated effort involving several research organizations. This is clearly the case with the high-power microwave program, where the tie between the Institute of Applied Physics in Gor'kiy and Lebedev Physics Institute in Moscow proved to be especially fruitful. The program appears to include a third partner, the complex of research institutes in Tomsk.

Development of high peak power gyrotrons are the focus of this national effort. Lebedev conducts no work on high average power devices outside of providing guidance to scientists at Gor'kiy and elsewhere. The high peak power machines have absolutely no application to the area of interest in gyrotrons in the West, for what is called electron cyclotron resonance heating of magnetically confined plasmas; their pulse lengths are too short and their repetition rates too low. The technology required for the high peak power devices differs qualitatively from the high average power gyrotrons, for example, their electron injection guns. The devices are not compatible.

The United States didn't start a serious program in high peak power short-pulse gyrotrons until 1984. Perhaps it was the density of Soviet reports of generation of pulses carrying tens of megawatts of power in 1982 and 1983 that finally got the United States moving (see Table 1 for a few of these Soviet results).

At the International Symposium of Gyrotron Development in Lausanne, Switzerland in July 1984 and through the *International Journal of Electronics* which published the conference proceedings, Victor L. Granatstein of the University of Maryland called for development of high peak power gyrotron devices, beginning with a gyroklystron amplifier that would produce pulses of 10 gigahertz microwaves with a peak power of 300 megawatts and a pulse length of 100 nanoseconds. To explain the physics problems and feasibility of such a device, Granatstein referred almost exclusively to Russian work in the area. Although Granatstein argued for his proposal on the basis that such devices could power new high energy particle accelerators more efficiently than existing microwave sources, the Air Force Office of Scientific Research and the Navy are providing a good chunk of the funding for the development program, which has generated a stream of scientific papers since Granatstein's 1984 address.

TABLE 3

Russia has steadily increased the number of its scientists devoted to gyrotron research

pre-1973	<20
1973-78	40
1982	78
1986	120

Source: S. Kassel, "Soviet Development of Gyrotrons," Rand Corp. Report R-3377-ARPA, May 1986.

Also, in 1984 Lawrence Livermore National Laboratory stepped up a program whose announced purpose is to develop high peak power, nanosecond pulses of microwaves and investigate the effects of microwaves on electronics. Recently, Livermore investigators generated a burst of microwaves with a peak power greater than 4,000 megawatts for 25 nanoseconds at 7 gigahertz with an efficiency of about 1%. It is not clear, however, whether the device, known as the vircator, dependent as it is on a 400,000 megawatt electron beam source, can be made transportable.

Granatstein argues that there is an advantage in developing high peak power gyroklystron amplifiers since the coherence of the output microwave radiation is expected to be much greater from an amplifier than from a gyrotron oscillator itself. High phase coherence is important for accelerator applications as well as radio-biological warfare. The Russians plan to stabilize the coherence of their oscillators by filling them with a low density plasma. To take this discussion further, it is necessary to describe the elementary physics of the gyrotron and other cyclotron resonance masers.

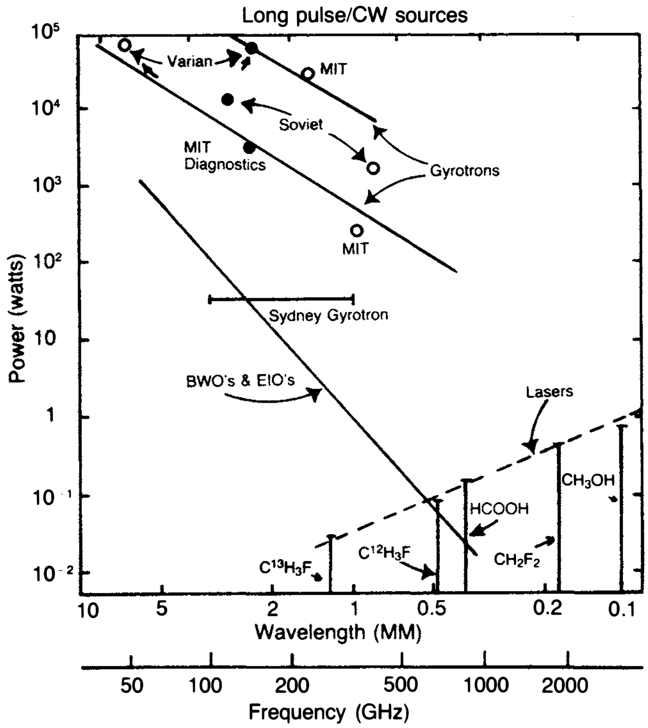
'Free electron' devices

The radio frequency portion of the spectrum of electromagnetic radiation ranges from extremely low frequencies whose wavelength is measured in kilometers through the microwave portion of the spectrum, named after the category of devices that produce radiation with gigahertz frequencies and wavelengths ranging from tens of centimeters to less that one millimeter. It is the judgment of scientists in both Russia and the United States that microwave devices or "tubes," will bridge the gap from the range of wavelengths achievable at reasonably high power with molecular lasers to those already reached at high power and efficiency with existing microwave tubes. **Figure 3** shows graphically the dramatic fall-off in existing molecular lasers' output power at long wavelengths. At a wavelength of 0.1 millimeters (100 microns), molecular lasers only produce a power of 1 watt. This submillimeter region is where the operating ranges of microwave tubes and lasers will overlap.

Unlike lasers, which are based on the emission of radiation from electrons bound to an atom or molecule, microwave tubes generate radiation from swarms or beams of "free elec-

FIGURE 3

The 'catastrophic chasm' in the electromagnetic spectrum



Gyrotrons and free electron lasers are expected to bridge the gap between the frequencies of radiation produced by lasers and those produced by conventional microwave devices (CW = continuous wave).

Source: R.I. Temkin, "High Frequency Gyrotrons,", in *Proceedings SPIE*, Vol. 666, 1986.

trons" moving through electromagnetic fields. Perhaps the most commonly known free electron device or microwave tube is the magnetron, the mainstay of Allied radar equipment in World War II and now the power source for everyday household microwave ovens.

We are interested in a more advanced subset of microwave tubes known as cyclotron resonance masers (CRM), which include gyrotrons, the so-called free electron laser, and other devices. (As its inventor, Hans Motz, points out, what is today called the free electron laser is not a laser at all, but simply an advanced microwave tube; he named it the "undulatron," after its action in undulating or oscillating its electron beam's trajectory.)

Cyclotron resonance masers are based on two facts of physics:

1) that high speed electrons emit radiation when they are turned; the frequency of radiation is proportional to the electrons' radius of curvature but Doppler-shifted with respect to their forward velocity; and

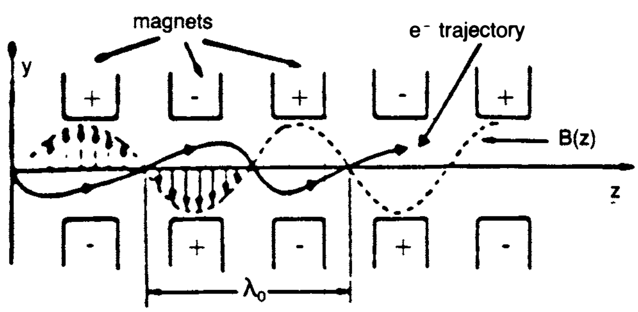
2) that beams of electrons directed into an electromagnetic field will form into bunches, phased at the Doppler-shifted wavelength of the field; these bunches will emit radiation of the same wavelength coherently.

In the free electron "laser," a beam of relativistic electrons is directed between a series of permanent magnets whose North-South polarity alternates, thus forming a standing periodic magnetic field variation or wave (**Figure 4**). In the reference frame of the electrons, the high beam velocity transforms this periodic magnetic field variation into an electromagnetic wave, which bunches the electrons at intervals equal to the Doppler-shifted spacing of the magnets. The magnets oscillate the trajectory of the electron bunches and the electrons emit radiation. (For a more detailed discussion see *EIR*, Nov. 7 and Dec. 12, 1986, and April 3, 1987.)

In a gyrotron, an electron gun or accelerator directs an electron beam into a resonant microwave cavity. A homogeneous magnetic field parallel to the forward direction of the beam turns the electrons in circular orbits as they would be in a cyclotron. Combined with their forward velocity, this rotation results in a helical motion of the electrons into and through the resonant cavity, as shown in **Figure 5.** Russian scientists believe that in optimal gyrotron operation, the transverse velocity of the electrons in their circular orbits should equal their forward velocity through the cavity, describing a helix with a pitch of 45°.

In the reference frame of the electrons, their helical motion inside the resonant cavity, transforms the homogeneous magnetic field into an electromagnetic field oscillating at the frequency of the electron's rotation, that is, the rotating electrons "see" an oscillating field, not a static one. The oscillat-

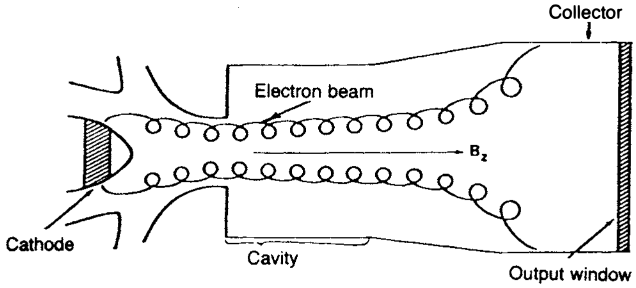
FIGURE 4



The undulator or wiggler for a free electron laser is composed of magnets of alternating polarity in a linear arrangement. An electron beam is directed down the center of the device, which turns the electrons alternately from north to south, thus oscillating their trajectory as shown. As the electrons turn, they emit electromagnetic radiation. The dotted line shows the shape of the periodic magnetic field that oscillates the electrons; the solid line shows the electron trajectory produced by the oscillation, as currently understood.

Source: M. Billardon, et al., "Free Electron Laser Experiment at Orsay: A Review," *IEEE Journal of Quantum Electronics*, Vol. QE-21, 1985, page 805.

FIGURE 5
Diagram of a gyrotron oscillator



Source: *International Journal of Electronics*, Vol. 57, No. 6, 1984, page 790.

ing field bunches the electrons at intervals equal to its wavelength, Doppler-shifted by the relativistic factor of the electrons' velocity (the ratio of an electron's kinetic energy to an electron's rest energy, plus 1). The electron bunches emit radiation at a frequency of approximately $\omega = (neB/\gamma m_0)$, where e and m are the electron charge and mass, B is the magnetic field strength, γ is the relativistic factor and n is the harmonic of the emission ($n = 1$ the fundamental; $n = 2$ is the second harmonic, etc.).

In a properly engineered device, the microwave cavity resonates in a mode compatible with oscillations at this frequency and guides the emission to the output window. In high frequency gyrotrons, the traditional closed resonant microwave cavity is replaced with mirrors between which the microwave radiation oscillates; these are called quasi-optical gyrotrons.

The basic components of a gyrotron are thus the electron source, the resonant cavity and output waveguide, the magnets, and the power supply for the electron source and magnets. The resonant cavity is itself tiny, with dimensions measured in centimeters. Transportable high peak power gyrotrons require compact, pulsed power sources and compact, intense relativistic electron beams (IREB), technologies where the Russians have a considerable lead. For example, the Neptun-2 accelerator used in gyrotron research and development at Gor'kiy, is reportedly a more compact version of the Neptun accelerator designed by Leonid Rudakov at the Kurchatov Atomic Energy Institute. The original Neptun occupied a few cubic meters of volume. A high peak power gyrotron with a more compact Neptun-2, a pulsed power source and solenoid magnets, could fit inside a medium-sized truck.

Soviet special forces operating out of such trucks in Western Europe could disable NATO aircraft, missiles, and tanks in the event of war before they could get off the ground, be fired, or leave their command posts. More important, radiobiological warfare special forces could wipe out entire officer corps, divisions, battalions, etc.

To be continued.