SAND93-2743C
Conf-940531--3

# SANDIA NATIONAL LABORATORIES' HIGH POWER ELECTROMAGNETIC IMPULSE SOURCES


L. F. Rinehart*, M. T. Buttram, G. J. Denison, J. M. Lundstrom,
W. R. Crowe, J. F. Aurand, P. E. Patterson
Dept. 1248
Sandia National Laboratories
Albuquerque N.M. 87185 USA



## ABSTRACT

Three impulse sources have been developed to cover a wide range of peak power, bandwidth and center frequency requirements. Each of the sources can operate in single shot, rep-rate, or burst modes. These devices are of rugged construction and are suitable for field use. This paper will describe the specifications and principals of operation for each source.

The sources to be described are: SNIPER (Sub-Nanosecond ImPulsE Radiator), a coaxial Blumlein pulser with an in-line (series) peaking switch; EMBL (EnantioMorphic BLumlein), a bipolar parallel plate Blumlein with a crowbar type (parallel) peaking switch; and the LCO (L-C Oscillator) a spark-switched L-C oscillator with damped sinusoidal output.

SNIPER and EMBL are ultra-wideband (UWB) sources which produce a very fast high voltage transition. When differentiated by the antenna, an impulse whose width corresponds to the transition time is radiated. The LCO operates with a center frequency up to 800 MHz and up to 100 MHz bandwidth. Because the LCO output is relatively narrow band, high gain antennas may be employed to produce very high radiated field strengths.


## The UWB SNIPER Source

SNIPER is a 250 kV ultra-wideband source producing 1.25 GW peak power into a 50 ohm load. The oil-insulated Blumlein is switched by a hydrogen gas spark gap. Hydrogen exhibits very fast dielectric recovery[1], allowing full power operation at >1 kHz and reduced power (power supply limited) operation up to 5 kHz. Figure 1 is a longitudinal section view of the SNIPER Blumlein and peaking switch. The output pulsewidth is 3 ns FWHM. Ultra-wideband frequency components are added to the pulse by sharpening the leading

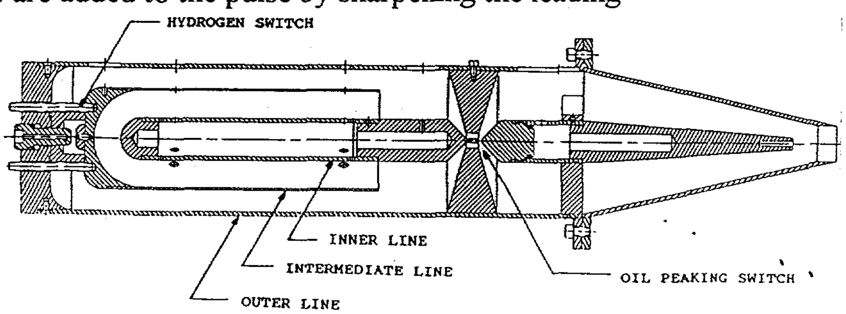


Figure 1. Cross Section of the SNIPER Blumlein and Peaking Switch

## DISCLAIMER

## DISCLAIMER

edge with a series peaking switch. The oil dielectric peaking gap in the center conductor of the coaxial Blumlein output sharpens the leading edge of the pulse to <200 ps. This switch operates at an electric stress level as high as 15 MV/cm to produce the fast risetime. The oil switch is purged several volumes per shot. However, because its' volume is very small, a modest flow of a few liters per minute is adequate even at 1 kHz rep-rate.

Two parameters characterize the peaking switch operation. These are lag time to breakdown and risetime. Lag time is defined as the time between voltage application and switch closure; risetime is the voltage fall time across the switch. Both are a strong function of electric field[2]. Figure 2 shows lag time to breakdown for unbiased transformer oil. The triangle data points are from an earlier study by Proud and Huber[3]. The dots and diamonds are from Sandia's experiments using undisturbed and flowing oil respectively. At full power, the SNIPER source operates at ~15 MV/cm on the flowing oil line.

Figure 3 shows the SNIPER output waveform, A., the Blumlein output with the peaking switch shorted, and B., with the peaking switch operating. The waveform with the sharpened leading edge has a 10-90% risetime of 300 ps before correction for instrumentation bandwidth. After correction the risetime is <200 ps.

The Blumlein and modulator fit into a 45 cm diameter by 75 cm length cylindrical container. Normalized radiated field strengths (measured in the far field and extrapolated back to 1 meter range) of 120 kV/m have been measured for SNIPER. Normalized field strength is a convenient parameter; the electric field at any range may be determined by dividing this number by the range.

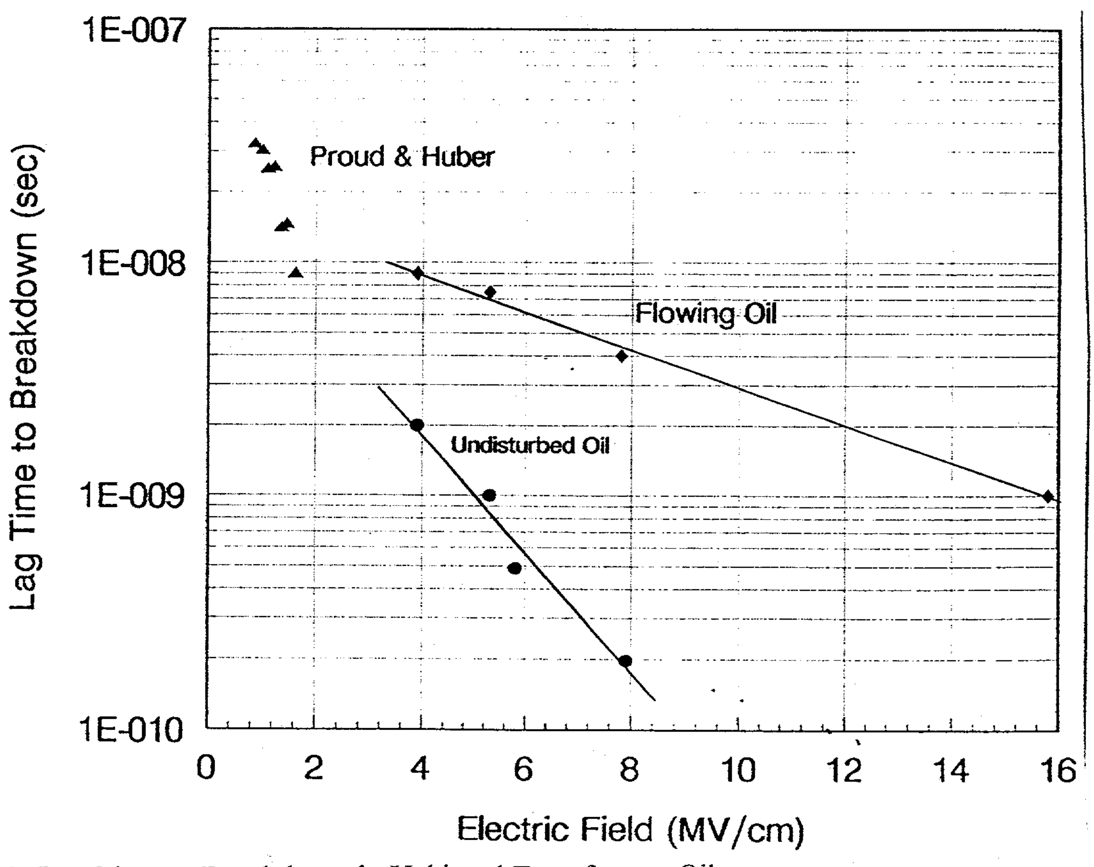


Figure 2. Lag Time to Breakdown in Unbiased Transformer Oil

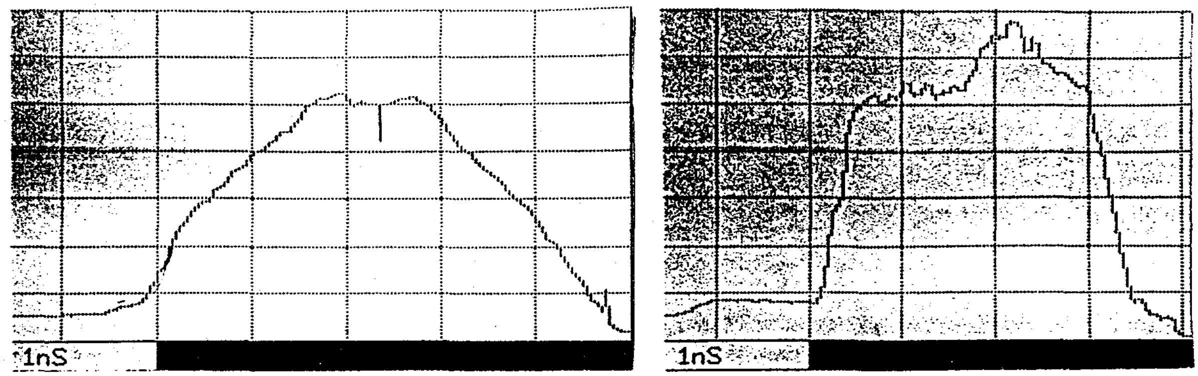

Figure 3. SNIPER Blumlein Output; A. Without Peaking Switch, B. With Peaking Switch

High Power UWB EMBL Source

The EnantioMorphic (mirror image) BLumlein, EMBL, operates at 750 kV to produce >11 GW peak power into 50 ohms. EMBL is a four line, single switch arrangement of two oppositely charged parallel plate Blumleins. See Figure 4. The Blumleins are in a "Marxed" configuration in which they would share a (fifth) ground line between them. The two lines would erect in opposite polarities with respect to this line. Since both the charging and output are bipolar, an actual ground line is unnecessary. Instead, the ground line is omitted and exists as a virtual ground plane. This plane is also a plane of symmetry, the two Blumleins being mirror images above and below it. Advantages of the parallel plate construction are that the switch geometry is simple and no balun is required to connect to an antenna.

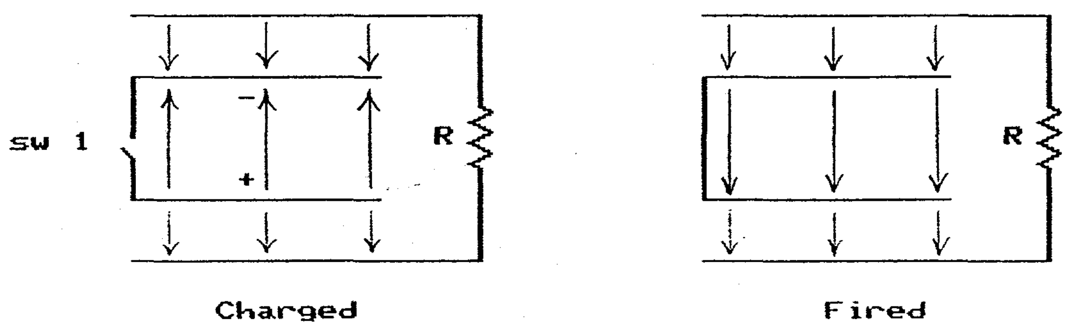

Figure 4. Bipolar EMBL Blumlein with E Vectors Shown, A. Line Charged, B. Line Erected

An additional advantage of the EMBL design is the use of bipolar charging. Impulse sources have inherently small energy storage capacity. A very significant efficiency problem exists because the stray capacitance of the charging circuit can be equal to or greater than the energy storage capacitance of the source. So a large fraction of the energy is then stored in stray capacitance and wasted. With bipolar charging, full charge voltage only appears across the impulse source. All stray capacitances are charged to plus or minus 1/2 full voltage. All else being equal, energy is stored in the strays at 1/4 th the rate of a unipolar charged device[4].

The device stores 50 to 75 Joules per shot, and rep-rate is power supply limited to ~700 Hz in 1 second bursts (40 kW ave. power during the burst).

A typical EMBL Blumlein output pulse is 3.5 ns FWHM. The pulse is crowbarred at peak voltage by a gas spark gap so that its' trailing edge is sharpened to <200 ps. Figure 5 shows the output pulse; the peaking switch crowbars the pulse just as it reaches full voltage. There is essentially no difference in spectral content between sharpening the leading or trailing edge of the pulse. Shorting the pulse with a shunt type peaking switch produces a much "cleaner" impulse output than the series type switch used in SNIPER. The shunt switch diverts all the late time ringing of the Blumlein and modulator from the antenna, allowing it to radiate only the UWB impulse.

Figure 6 is the radiated impulse from EMBL. Note that it is the derivative of the "peaked" waveform in figure 5. The impulse width is the fall time across the peaking switch plus some

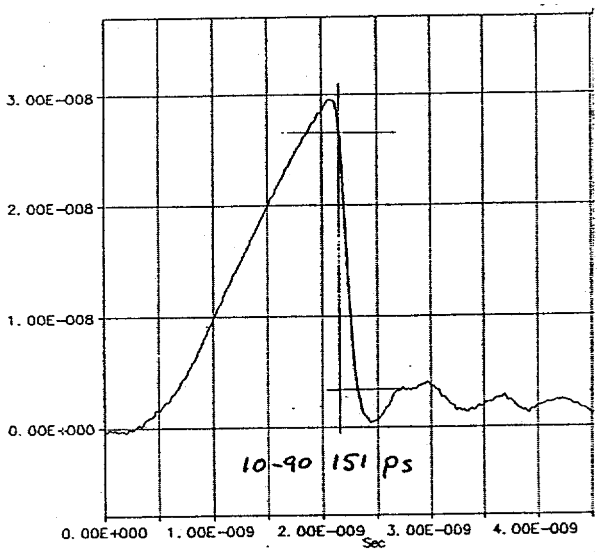


Figure 5. EMBL Output Voltage Waveform
Vertical: Arbitrary Voltage Units
Horizontal: 500 ps/div.

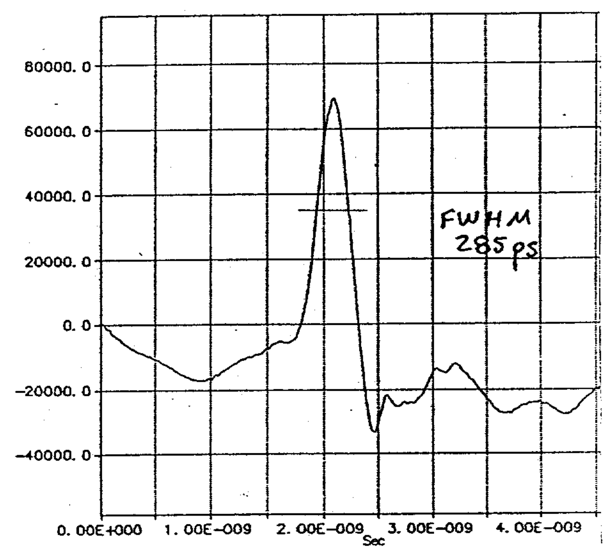


Figure 6. Radiated E-Field
Vertical: Received Far Field (V/meter)
Horizontal: 500 ps/div.

smearing by the transmit and receive antennas. Pulse smearing in the antenna is a geometric factor. It is farther from the input terminals to the outside corners of the TEM horn aperture than to the center, so the wave is not launched simultaneously across the aperture. A difference of a few centimeters distance across the aperture can smear the pulse by 100 ps. Pulse smearing accounts for the difference between the voltage fall time in figure 5, and the impulse width in figure 6. The 3 dB bandwidth of the radiated pulse extends from 0.2 to 1.2 GHz, and is peaked at 800 MHz. EMBL's normalized radiated field strength is as high as 380 kV/m. The EMBL Blumlein, peaking switch, and modulator fit in a 40 cm square by 1.7 m long container.

## The LCO Wideband Source

The LCO transmitter employs a spark switched "pancake" L-C oscillator (LCO) to directly drive a 1/2 wave dipole[5]. These devices operate over a wide range of center frequencies from HF to UHF. The LCO is a self-resonant R-L-C circuit. It comprises two disc shaped parallel plates which form the capacitor and a spark gap switch which penetrates the dielectric between the plates. Figure 7 shows a cross section of a typical LCO, in this case a 700 MHz oscillator. The geometry of the plates and spark gap determine the circuit inductance.

A typical schematic is represented in figure 8, in this case the component values are for a 50 MHz center frequency. The most efficient antenna match is achieved when the L-C oscillators' characteristic impedance, Zo, is much greater than Rs, the series loss (spark gap heating), and much less than Rp, the parallel loss (the antenna). The optimum characteristic impedance is on the order of 10 ohms[6].

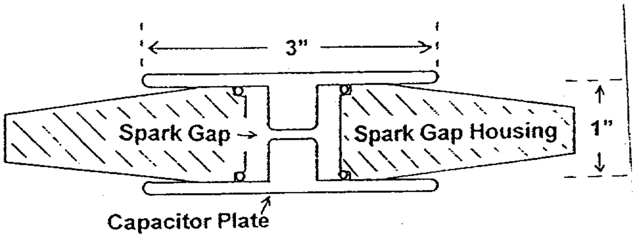


Figure 7. Cross Section of 700 MHz LCO

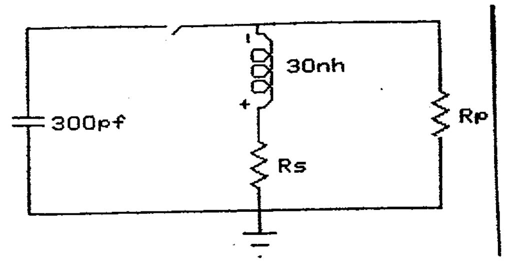


Figure 8. Schematic of a 50 MHz LCO

At VHF and UHF frequencies, it may not be possible to construct the oscillator to withstand very high voltage (a few hundred kV) and keep the characteristic impedance as low as 10 ohms. This is because at high voltage the requisite dielectric thickness and switch size force the inductance up. Since the characteristic impedance is $Z_0=(L/C)^{1/2}$, there is a trade-off between high voltage capability and low impedance. If the oscillator impedance is too high it will be severely loaded by the antenna and Q may be very low.

The center frequency of the unloaded oscillator is shifted downward by the series and parallel losses. As the R-L-C circuit approaches critical damping, Q lowers, and the frequency spectrum widens and shifts downward. This frequency shift is significant and becomes a design consideration when Q is low (say $<3$)[6,7].

In the case of our 700 MHz transmitter, the LCO and dipole are situated at the focus of a parabolic cylinder sub-reflector, and the LCO/dipole and sub-reflector package is positioned at the focus of a larger (3.7 m diameter) parabolic dish. Overall gain for the system is 26 dBi with a 12 degree (3 dB) beamwidth. The modulator, L-C oscillator, dipole, and sub-reflector are enclosed in a plastic box filled with insulating gas (SF6). The device can run for several minutes at >1 kHz rep-rate. With the large parabolic dish reflector it produces normalized boresight E-fields in excess of 400 kV/m. Figure 9 shows the radiated E-field and frequency spectrum.

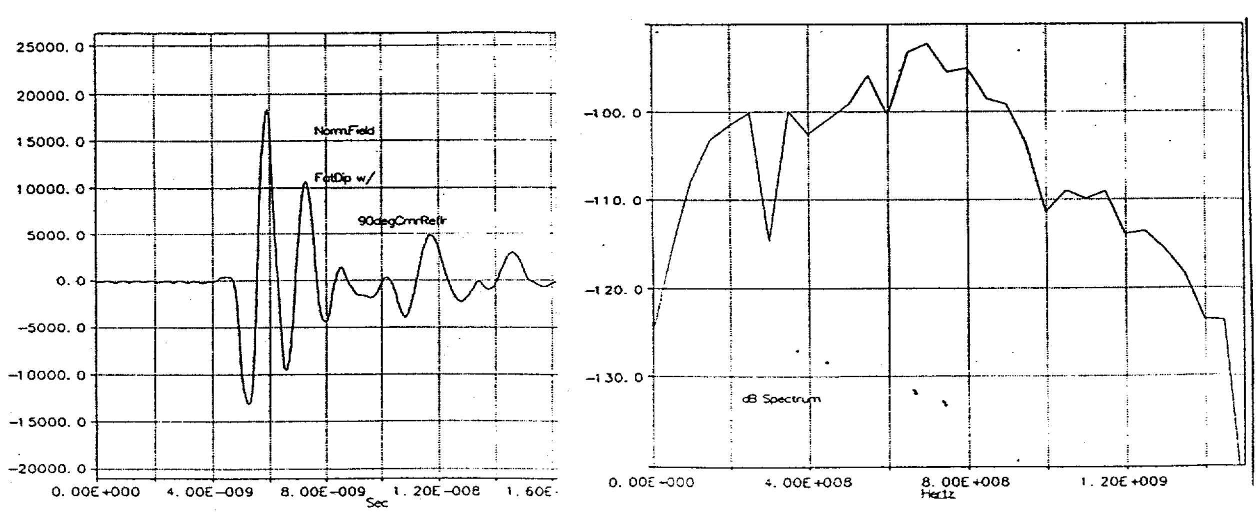


Figure 9. Radiated E-Field and Frequency Spectrum of a 700 MHz LCO

Corona Losses on Antennas

Corona exists near the surface of high voltage conductors and extends out to a distance where the electric fields fall below 30 kV/cm for atmospheric pressure air. Corona losses occur primarily because moving ions collide with neutral gas particles and increase the thermal energy of the gas[8].

When very high voltage is applied to the antenna, losses to corona loading can be surprisingly severe. Figure 10 shows how serious this problem can be. The EMBL pulser is connected to a 4 meter long TEM horn antenna with a 1.3 meter wide aperture. This antenna has a tapered solid plastic insulator in the feed section, so arc formation cannot occur without leaving direct evidence. We are assured that the losses are due only to corona and partial discharges.

The horizontal axis in the figure represents the EMBL firing voltage which approximates voltage at the antenna terminals. The vertical axis represents the corresponding normalized radiated peak power density. The diamonds are data points with the antenna in air. The normalized power density at 750 kV operation is <150 MW/meter$^2$.

One means of reducing corona losses is to enclose the high field portions of the antenna in an insulating gas. The dots are data points where the first meter of the TEM horn plates are in sulfur hexaflouride. The corona inception field strength for SF6 is 88 kV/cm at one atmosphere. With SF6 in the feed section of the horn, power density increases to >350 MW/m$^2$, an improvement of >100% at the same voltage. The solid line in figure 10 shows normalized power density for a lossless system.

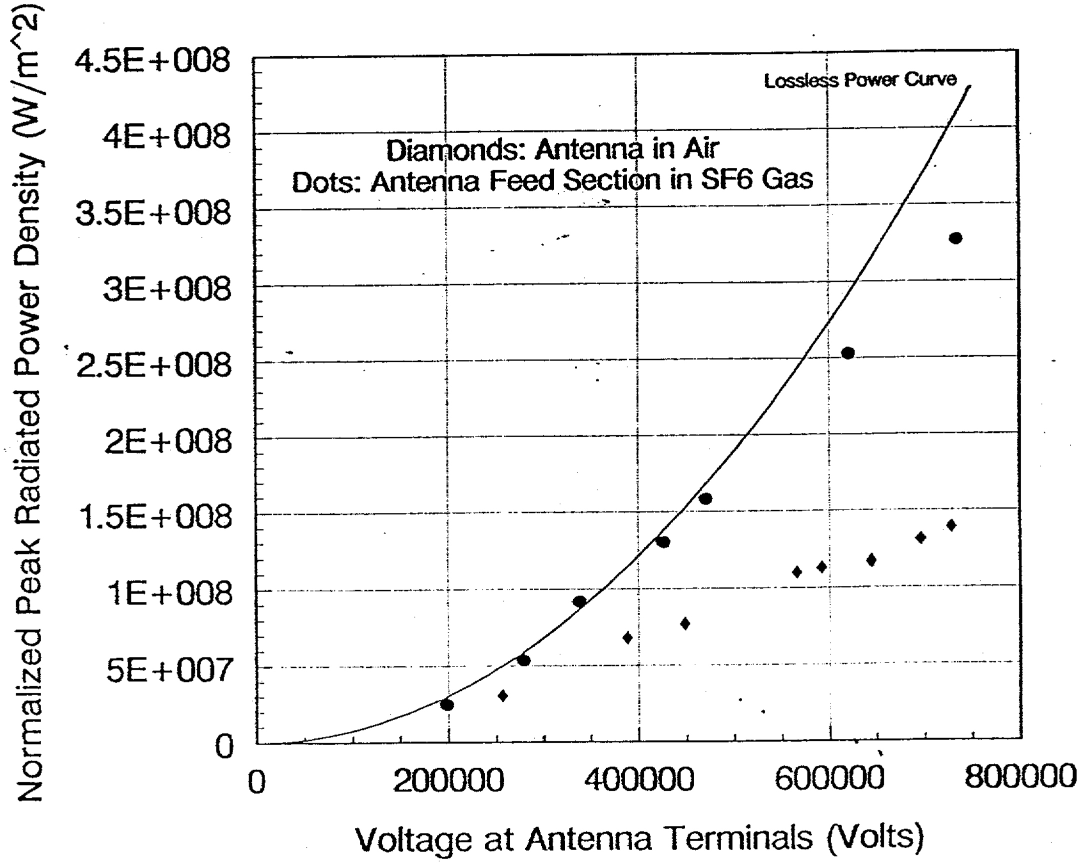


Figure 10. Radiated Power Loss to Corona Loading of the Antenna

SUMMARY

Three impulse sources have been constructed and deployed for field testing. They produce normalized radiated electric fields as high as 400 kV/m with repetition rates as high as 1 kHz. Waveforms are either unipolar impulses as in the case of SNIPER and EMBL, or a damped sinusoid for the LCO source.

References

1. S. L. Moran and L. F. Rinehart, Voltage Recovery Time of Small Gas Spark Gaps, IEEE Transactions on Plasma Science, Dec. 1982, Vol. PS-10, No.4

2. J. W. Ginn, D. N. Hendricks, and M. T. Buttram, Nanosecond Spark Gap Measurements, 17th IEEE Power Modulator Symposium, June 1986

3. J. M. Proud and H. J. Huber, Picosecond Risetime Switch Study, Technical Report No. RADC-TR-67-400, Rome Air Development Center, August 1967

4. L. F. Rinehart, M. T. Buttram, W. R. Crowe, R. S. Clark, J. M. Lundstrom, P. E. Patterson, An Enantiomorphic Blumlein Impulse Generator, 20th IEEE Power Modulator Symposium, June 1992

5. L. F. Rinehart, J. F. Aurand, J. M. Lundstrom, C. A. Frost, M. T. Buttram, P. E. Patterson, and W. R. Crowe, Development of UHF Spark-Switched L-C Oscillators, 9th IEEE Pulsed Power Conference, June 1993

6. S. L. Moran, High-Repetition Rate L-C Oscillators, U.S. Naval Surface Weapons Center Technical Report, NSWC/DL TR-3658, December 1977

7. F. E. Terman, Radio Engineer's Handbook, pp. 145-148, McGraw-Hill, New York, 1943

8. J. D. Cobine, Gaseous Conductors, Dover Publications, Inc. 180 Varick St., New York, N. Y., 10014, 1958