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USES OF INTENSE ELECTRON BEAMS

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INTRODUCTION

The last survey talk on this subject was presented by S. E. Graybill at the Chicago Accelerator Conference four years ago. He described, in general, the basic aspects of high power pulsed electron beam technology utilizing field emission diodes and outlined the current status of work in this area; with particular emphasis on beam handling and propagation with magnetic guide fields and also the utilization of intense electron beams for the collective acceleration of ions. Other applications were mentioned in passing and in his conclusions, Graybill summarized the situation at that time with the observations that (1) the production and handling of pulsed relativistic electron beams are in good shape technically, but (2) the theoretical and experimental application of such intense beams is still in its infancy.

During the past few years, there has been a rapid escalation of work in many laboratories on a broad front of exciting new applications, and there has been rapid progress in a variety of areas - I would mention, in particular, work in the United States, England and the Soviet Union.

By intense beams, I mean power levels of 10^{11} W to a few terawatts (few x 10^{12} W) with currents over 50 kA to megamperes with electron energies from a few hundred keV to nearly 15 MeV.

While the basic technology was indeed in good shape four years ago, to meet the specific needs for the various new applications, there has been substantial progress in technology improvements. These improvements relate mostly to pulse power machines having low impedance (in the 1 Ohm range) to produce very high currents with emphasis on improving the acceleration of the beam power, i. e., reducing the risetime of the current. In this review, I will try to summarize both the current status of the technology and the main results of those experiments which relate to applications which are now receiving the most attention. In this country, it might be mentioned that the main support has come from the Defense Nuclear Agency and the United States Atomic Energy Commission - now part of ERDA.

APPLICATIONS

The following is a list of the main applications:

Applications of Relativistic Electron Beams

- Flash X-ray Generators

- Controlled Thermonuclear Fusion
  Plasma Heating (electron and ion beams)
  Plasma Confinement (electron and ion beams)
  Pellet Fusion and and Physics of High Temperature, Dense Plasma

- Collective Ion Acceleration

- Excitation of High Power Lasers
  Noble Gas Excimer Lasers
  Transfer Lasers
  Chemical Lasers

- Microwave Generation

Flash X-ray Generators

Flash x-ray technology utilizing relativistic electron beams was pioneered in England under the guidance of J. C. Martin. Specific applications of interest include flash radiography and material response to ionization by intense gamma rays. There is no need to dwell on this subject here because it is covered in another paper at this Conference entitled "A 9 MeV Pulsed Electron Accelerator with an Intensely Focused Beam" by Champney and Spence. Suffice it to say that for such applications voltages above a few megavolts are required at relatively high impedance values - 30 - 100 Ohms are typical. For such high values of impedance, oil filled pulse lines in the so-called Blumlein configuration are generally employed with pulse durations of the order 100 ns.

Controlled Thermonuclear Fusion

Magnetically Confined Fusion Plasma

There is some interest in evaluating the use of intense beams for both heating and confinement and magnetic confinement of a fusion plasma. First, with regard to the heating of low density plasmas, experiments carried out at Novosibirsk, USSR, the Naval Research Laboratory, Cornell University, Physics International and the Sandia Laboratories, Albuquerque served to demonstrate anomalous (greater than classical expectations) beam-plasma coupling for densities in the range 10^{12} - 10^{16} ions/cm^3. The data indicates that the coupling is strongest when the particle density of the electron beam is comparable to the plasma particle density. Fairly complete documentation, including electron energy measurements from Thomson scattering for the case of weak coupling, has only been carried out at NRL. In those experiments, D. Hammer and G. Goldenbaum showed that the electron temperature increases by about 20 eV, which was large compared to the initial temperature prior to injection of the beam. Here, the initial plasma density was much greater than the beam particle density. In the low density regime, much more work needs to be done in order to understand the physical mechanisms involved in the transfer of energy from the beam to the plasma. Ion accoustic wave instabilities produced by return currents in the plasma, as well as two-stream instabilities, are most likely important.

Another application related to magnetic fusion is the utilization of intense, pulsed electron or ion beams to produce current layers in a magnetic trap which result in closed magnetic field lines. Demonstration of field reversal on the axis of the magnetic trap, and, hence, closed magnetic field lines, has been demonstrated by H. Fleischmann at Cornell University. The basic concept is due to N. Christofilos, who attempted to achieve field reversal by repetitively pulsed electron injection in the well-known ASTRON experiments at the University of California's Lawrence Livermore Laboratory. In such experiments, the electron beam serves to both heat and confine plasma. The 5 MeV, 150 kA machine used at Cornell is shown in Figure 1.

The application of pulsed electron beams to form electron rings for ERA (electron ring accelerators) is discussed in several other papers at this Conference.

Electron Beam Initiated Pellet Fusion

Serious experimental programs to achieve fusion by electron beam-driven pellet implosions are in progress at Sandia, under the direction of G. Yonas, and at the Kurchatov Institute for Atomic Energy in Moscow, under the direction of L. Rudakov.

So far, about 10 kJ of beam energy has been deposited on millimeter targets, and it is reported by Sandia that the observations indicate spherically symmetric energy absorption and implosion. From a theoretical point of view, it appears that in the absence of electron range shortening due to anomalous (non-classical) absorption of the electron energy by the target above 10^{14} watt at a few MeV is required for break-even (thermonuclear energy released comparable to electron energy absorbed). Short pulses are required because of short disassembly times. Recognizing that there are many uncertainties in the theory, it is, however, still possible that power levels below 10^{14} W would produce substantial fusion yields and, in any event, would be useful in the understanding of the scaling laws which govern the production of dense high temperature plasmas at or near fusion temperatures.

Additional information concerning "Acceleration Needs for the Fusion Program" was presented by R. Sudan at this conference.

Collective Ion Acceleration

Linear collective acceleration of ions to energies higher than that of the relativistic electrons injected into a gas was first observed by S. Graybill and J. Uglum at Ion Physics about five years ago and shortly thereafter by J. Rander, B. Ecker, G. Yonas and D. Drickey at Physics International where magnetic analyses and nuclear emulsion measurements were employed. At Ion Physics, the ion time of flight technique was used to measure the ion energies.

Pulses with 10^{12} - 10^{13} protons have been accelerated to 5 - 10 MeV with 1 - 2 MV electrons. Proton currents of 100 - 200 A were observed. The local accelerating fields appear to be at least 30 MV/m, possibly as high as 100 MV/m. Further, high-Z nitrogen ions have been to still higher energies. About 10 A of nigrogen ions at ≈30 MeV have been reported.

Recent progress by C. Olsen (Sandia) in explaining these data is reported in the next paper. Briefly, the acceleration models used for theoretical analysis involve the formation of a potential well by the electron beam with a depth of order $(\gamma - 1)\, mc^2$, with an acceleration of the well that is closely connected with the propagation of a beam-induced ionization wave.

Excitation of High Power Lasers

Electron beams are now widely used to excite high pressure gases under circumstances where the collisional excitation and de-excitation are measured in nanoseconds and tens of nanoseconds. Compact low inductance accelerators with short risetime of the current are needed and have been developed during the past three years. A schematic picture of a 1 MeV, 100 kA (POCOBEAM) in routine use for laser studies at Livermore is shown in Figure 2.

The front end of the machine, the drift tube and laser chamber are shown in Figure 3.

By inserting a high pressure SF_6 switch between the output switch and the vacuum diode, the current risetime can be reduced to less than 5 ns (10-90%).

Another machine now in operation at Sandia-Albuquerque for laser studies produced about 200 kA at 2 MeV with a risetime of only 10 ns.

Noble Gas Excimer Lasers

Electron beam-induced lasing of xenon molecules in the liquid state that have a lower state with negligible binding energy (so that there is no bottleneck) was first reported by Basov and Danielichev at the Lebedev Institute. Vacuum UV radiation at about 1730 Angstroms was reported. Demonstration of the possibility of producing an intense vacuum UV laser then led to intensive efforts in a number of laboratories to produce laser action in high pressure gases. High pressures are required since it is likely that 3-body collisions are involved in producing the xenon excimers in a complicated reaction chain for which the rate coefficients are not completely known. In general terms, the electrons produced by electron beam-induced ionization generate excited xenon atoms which collisionally form excited xenon molecules. In a joint investigation between Maxwell and LASL, about ~1/2 GW of laser radiation has been produced with an efficiency above two percent and with gains of about 10%/cm. A 6 x 6 x 50 cm^3 chamber at about 7 atm was used.

Basic xenon experiments were also carried out at Livermore, Sandia and CEA/Limeil, France. Laser action in krypton at 1453 Angstroms and, most recently, in the visible from the oxides of xenon and krypton were reported by Livermore.

In the latter cases, the laser output power was substantial - of the order 100 kW. Some of the experimental results reported for excimer lasers follow.

Hughes, Hunter and Shannon observed nonlinear build-up or gain, as well as line narrowing at 1260 Angstroms in argon.

		e-BEAM	LASER
XENON	1730 Å	800 keV	8J in 20 ns
		80 kA	~500 MW
		60 ns	100 psia
KRYPTON	1453 Å	1. 6 MeV	10 ns
		8 kA	250-500 psia
		50 ns	
ARGON	1260 Å	800 keV	4-15 ns
		80 kA	300-1000 psia
		60 ns	
XeO AND KrO	~5570Å	1 MeV	10 mJ in 100 ns
		100 kA	100 kw
		50 ns	150-225 psia

Another class of lasers produced by electron beam excitation is transfer lasers. In a pioneer experiment by Searls and Hart at NRL about one year ago, gain was observed in an argon-nitrogen mixture. The process involves elastic scattering of electrons to produce excited argon atoms which collide in turn with nitrogen molecules - producing electronically excited N_2^*. Stimulated emission from the C state to the B state produces strong radiation, particularly at 3577 Angstroms.

Ault, Bhaumik and Olsen reported the first significant energy output, about 1 MW in a 7 ns pulse utilizing about 1 kJ of 1 MeV electrons. In a collaboration between W. Hughes (LASL) and R. Hunter (Maxwell), an 800 keV, 80 kA beam produced over 10 MW of laser power from Ar/N_2 in a 20 ns pulse.

Finally, it is worth mentioning that electron beams have been used to trigger volumemetric chemical reactions which led to inverted populations of HF molecules. In the first experiments of this type of R. Jensen and P. Robinson (LASL) and Kolb (Maxwell), about 1 gigawatt of near-IR radiation was produced about two years ago at moderate pressures of SF_6 with ethane. A 500 kA beam contained by a magnetic field was employed. More recently, Sandia and LASL reported an experiment in which about 40 GW (≈2000 J) was generated in a mixture of hydrogen and flourine at 1 atm. A 2 MeV, 50 kA beam was employed.

Thus, it is now apparent that relativistic electron beams have already opened up an entire new technology for the generation of intense laser beams over a broad band of wave lengths ranging from the vacuum UV to the near-IR.

Microwave Generation

Another exciting application pioneered by J. Nation at Cornell University, and later at the Naval Research Laboratory, Lebedev Institute and Kharkov is the generation of intense microwave beams. There are several mechanisms which may be employed for the production of microwaves by electron beams as outlined below.

ELECTRON BEAM-
MICROWAVE GENERATION MECHANISMS

Relativistic Electron Cyclotron Maser	(X-band and mm bands)
Efficiency 1-2%	Cornell, NRL
Theoretical Limit 10%	NRL
Periodic Structure and e-Beam	(X-band)
Efficiency 10-20%	Lebedev, Cornell, NRL
Coherent Stimulated Raman Scattering	(sub mm bands)
Efficiency $\ll 1\%$	

High efficiency (over 10%) excitation using a periodic magnetic structure was first reported by Rabinovich and Rukadze (private communication).

Microwave frequencies and powers which have been reported are listed below:

MICROWAVE FREQUENCIES AND POWER LEVELS

BEAM ENERGY	BEAM CURRENT	DURATION	MICROWAVE FREQUENCY	MICROWAVE POWER
3 MeV	100 kA	80 nsec	7. 7 - 12. 4 GHz	1 GW
2. 5 MeV	50 kA	60 nsec	14 - 22 GHz	350 MW
2. 5 MeV	50 kA	60 nsec	22 - 40 GHz	10 MW
2. 5 MeV	50 kA	60 nsec	600 - 750 GHz	0. 1 MW

The highest power reported so far made use of the Cornell 5 MeV accelerator (operating at 3 MeV) shown in Figure 1. Peak power of 1 GW in the x-band was observed by V. Granatstein of NRL using the Cornell machine. The radiation was produced by electron cyclotron maser mechanism action. It is noteworthy that the wavelength range extends out to the far-IR as was demonstrated by NRL in experiments which produced about 100 kW at sub-millimeter wavelengths with coherent stimulated Raman scattering.

HIGH POWER ELECTRON BEAM MACHINE DESIGN

High power e-beam machines for specific applications are now designed by utilizing proven computer simulation techniques. Pulse lines with distributed values of characteristic impedance coupled to a diode with a beam having finite inductance and a time dependent impedance can be analyzed with high accuracy by computer simulation. An example of the good agreement between the calculated and measured waveforms of a 500 keV, 2 Ω machine is shown in Figure 6. These computer techniques were used to design a 1 terawatt machine located in Valduc, France. The observed waveforms, voltages and currents showed similar good agreement.

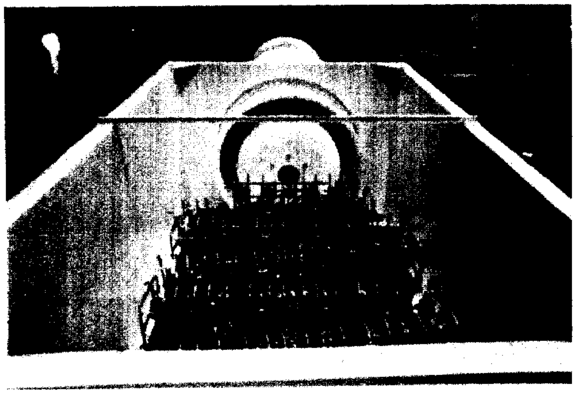

Figure 1. 5 Mev, 150 kA electron accelerator for studies of magnetically confined fusion plasmas. Marx generator in foreground and oil Blumlein at top.

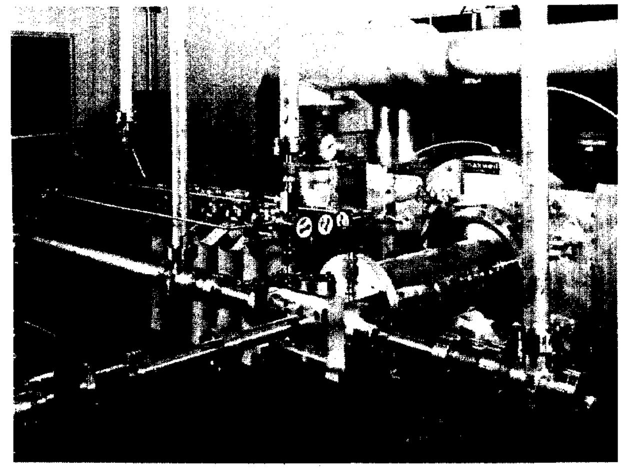

Figure 3. Drift tube and laser chamber shown schematically in Figure 2. (Photo courtesy of Lawrence Livermore Laboratory.)

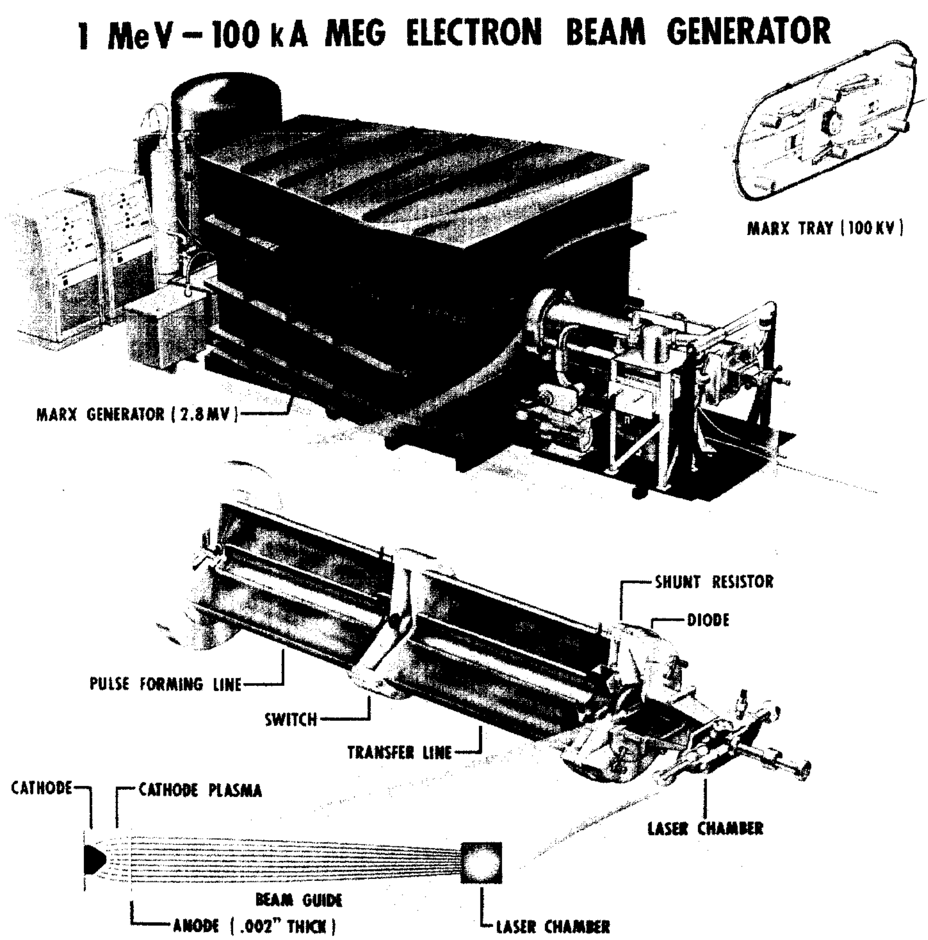

Figure 2. 1 MeV, 100 kA, 50 ns machine with a 15 ns risetime. High pressure SF_6 output switch, vacuum field emission diode, electron drift chamber and laser chamber, together with a water dielectric pulse line charged from a Marx generator. (Photo courtesy of Lawrence Livermore Laboratory.)

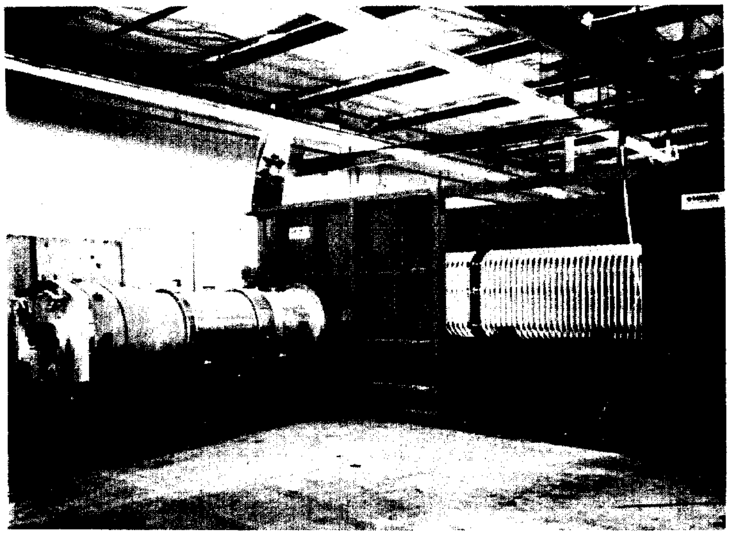

Figure 4. 2 MeV, 200 kA machine with 10 ns risetime used for laser studies at Sandia-Albuquerque. Beam width is 50 cm.

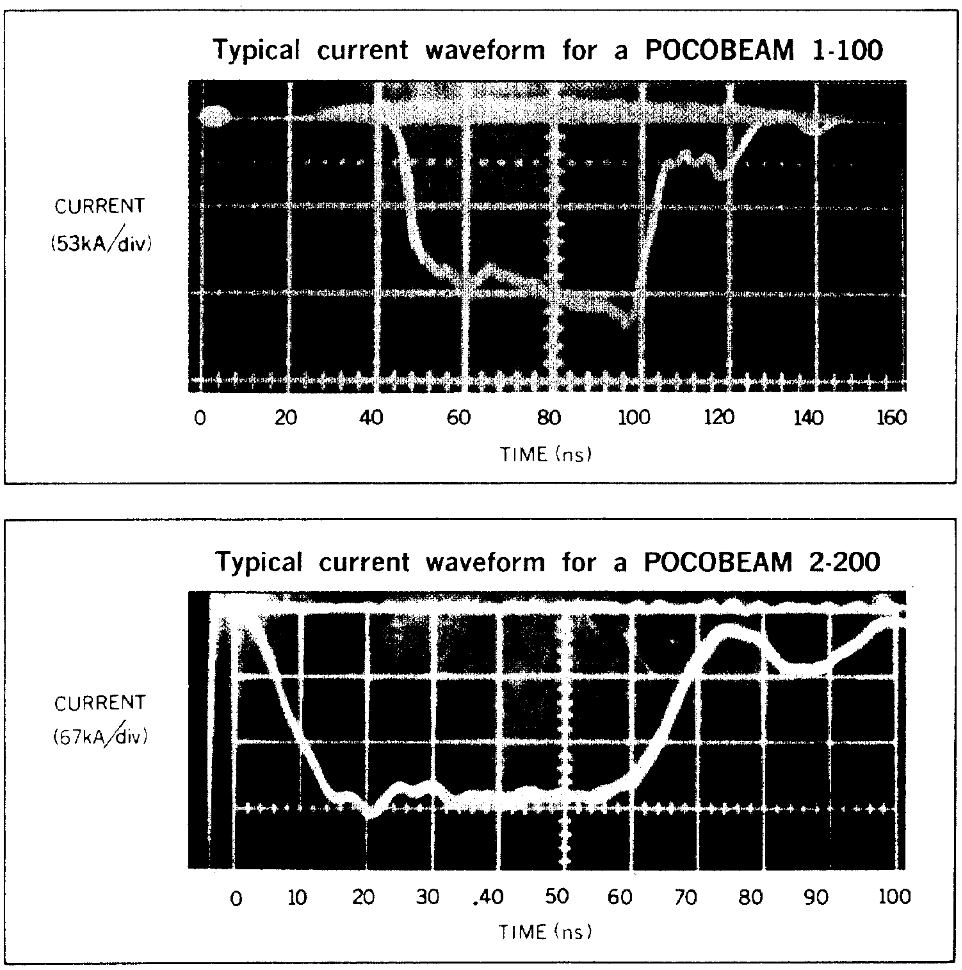

Figure 5. Current waveforms for 1 and 2 MeV, 10 Ohm machines used for laser excitation studies.

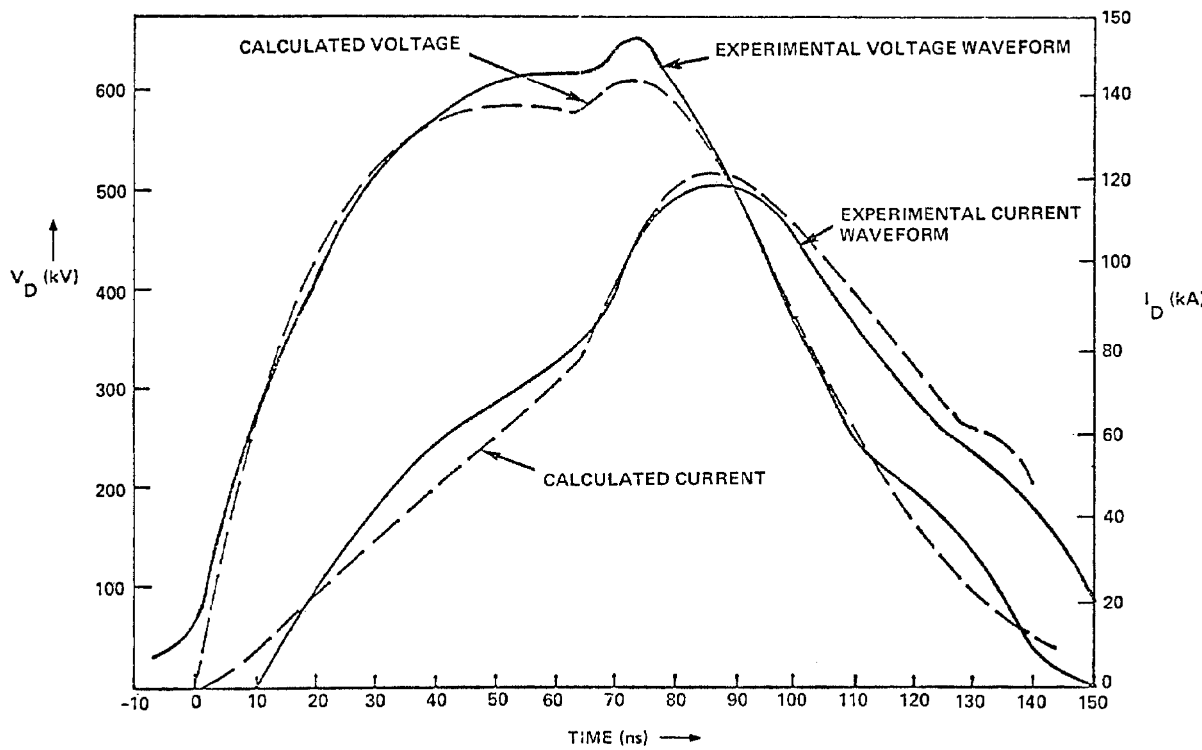

Figure 6. Typical diode voltage (V_0) and current waveforms (I_0) for 500 kV pulse generator.

Figure 7. 1 terawatt electron beam generator having a beam voltage $\gtrsim$ 1 MeV. A triggered multichannel 4 MV water switch is located in the dome-shaped section. To the right is an output transformer which reduces the voltage and raises the current to nearly 1 MA. (Photo courtesy of CEA-Valduc.)