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J. H. Hammer,
C. W. Hartman,
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A. W. Molvik

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Lawrence Livermore National Laboratory

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INITIAL SOFT X-RAY PRODUCTION EXPERIMENTS ON RACE

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Lawrence Livermore National Laboratory

Livermore, CA 94550

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ABSTRACT

Initial ring stagnation experiments on the Ring ACceleration Experiment (RACE) show photon fluences consistent with modeling (approximately a few kilojoules with $h\nu > 10$ eV) and an output time scale of the order of the shock heating time (5-10 μs).

In this report we describe the first experiments on soft x-ray production in the RACE device at LLNL. The RACE experiment[1] shown in Fig. 1 is a coaxial accelerator of magnetically confined plasma rings (compact toroids) that produces plasma velocities in the range $10^7 - 3 \times 10^8$ cm/s with directed kinetic energies from 4 to 40 kJ. RACE is a proof-of-principle scale device with the goal of demonstrating the feasibility of the compact-torus accelerator as a high-power density driver for many applications, including x-ray production.

Large-scale accelerators (~ 10's of MJ) could provide MJ's of x-ray flux in the 10 keV spectral region which is of interest for simulation of nuclear weapons effects. The method of converting compact torus kinetic energy into x-rays is closely analogous to the process in z-pinches[3]. The plasma ring, after acceleration to high velocity, impinges on a surface (a stagnation screen). This launches a strong shock wave back through the compact torus plasma. The shock wave heats the ions to high temperatures, which in turn heat the electrons through collisional equilibration. The electrons partially strip the ions and excite line radiation with characteristic photon energies of the order of the electron temperature. The efficiency of the process can be high and is predicted to be strongly dependent on the compact torus plasma properties: density; velocity; scale length and ion species.

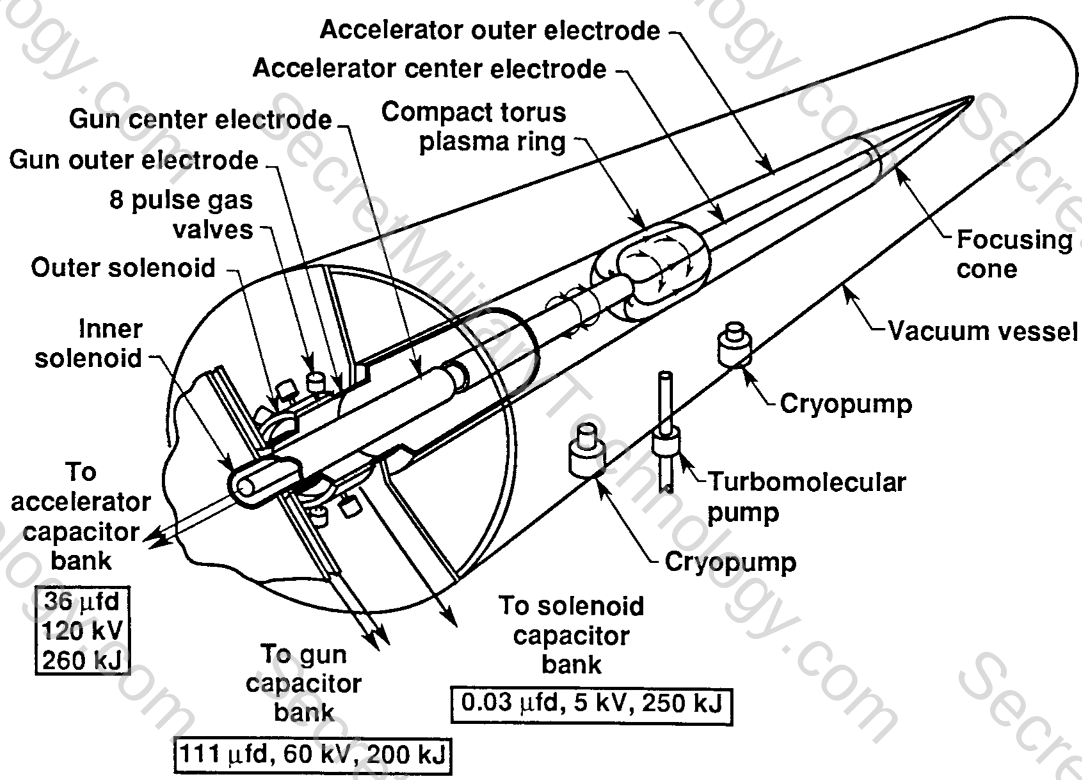

Fig. 1. The RACE experimental apparatus.

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Simulations predict that the mean photon energy for high conversion efficiency increases with plasma density and is highest when the compact torus is focused to small dimensions (~ a few cm). The preliminary tests of shock heating and radiation production in RACE have been conducted with unfocused rings. For these experiments, we have observed partial confirmation of the radiation process in that the onset of the radiation pulse is coincident with the arrival of the compact torus at the stagnation screen, the observed fluences are consistent with modeling (~ few kilojoules with $h\nu > 10$ eV) and the ouput time scale is of order of the shock heating time (5-10 μs).

The geometry of the stagnation region on RACE is shown in Fig. 2. The stagnation plate is 519 cm downstream from the gun muzzle/accelerator breech. The outer electrode and stagnation plate are composed of 53% transparent copper screen with 0.75 inch mesh spacing to allow diagnostic access. Two x-ray diodes (XRD's) on loan from the Air Force Weapons Lab at Albuquerque, NM were deployed so as to view the plasma near the impact plate as shown in Fig. 2. Note that the impact plate itself was not in the field of view of the diodes. Both diodes viewed the same volume of plasma, contained polished aluminum photocathodes, and were biased at -3000 volts. One of the diodes was unfiltered while the other was covered by a Kimfoil filter that effectively eliminated all photons of energy less than 200 eV.

For these experiments, the gun and accelerator were operated in a mode such that comparatively heavy and slow but well localized compact toroids were produced ($M \sim 10^{-3}$g, $v \sim 10^{7}$cm/s). Fast rings ($v > 10^{8}$ cm/s, $M \sim 10^{-5}$ g) produced no detectable signals on the XRD's as expected from the modeling for unfocused rings. Ring mass and speed are controlled largely through the timing and amount of gas inlet by the pulsed gas valves, (see Ref. 2 for a description of the RACE apparatus) although in the heavy ring case, much of the plasma in the rings is apparently derived from electrode surface

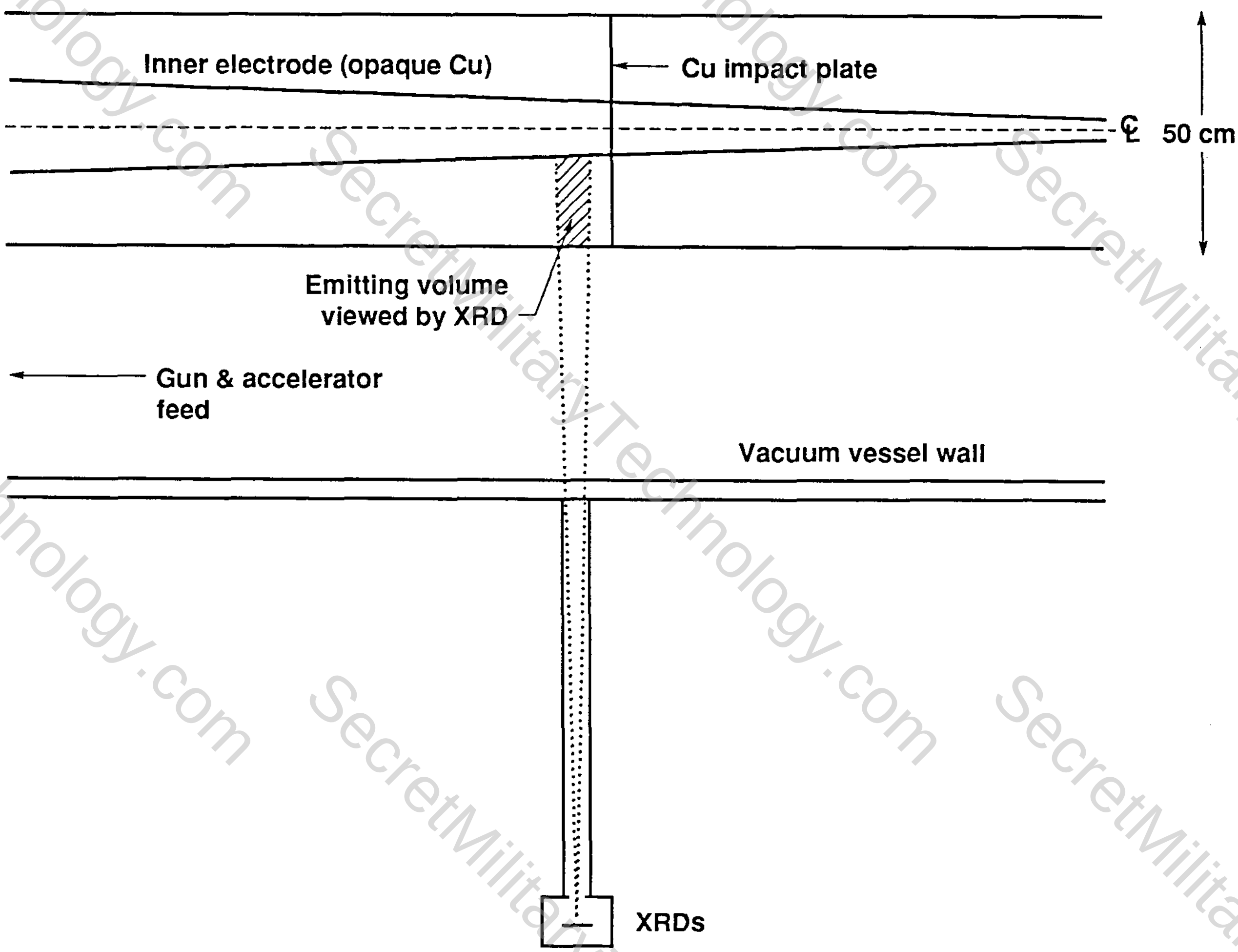

Fig. 2. Compact Torus impact region on the RACE experiment

contaminants -- mainly carbon and oxygen. The modeling of x-ray production indicates that carbon and oxygen are (fortuitously) about the right Z for good coupling of compact torus energy to photons for this ring parameter regime.

Compact torus properties were determined by magnetic probes, a HeNe laser interferometer, a visible light monochrometer and VUV detectors. The latter are similar in operation to the XRD's, with aluminum photo-cathodes and a bias voltage of -250 volts.

Many shots showed large signals (<10 volts) on the bare XRD although no signals were observed on the filtered XRD. The threshold for detection (2 mV) would require photon fluences with $h\nu > 200$ eV that are of the same order as the total fluence observed on the bare XRD, so it is consistent with the expected photon energies (few tens of eV) that no signals were observed on the filtered XRD. Table 1 shows the ring parameters for shot #3520.

Table 1 - Shot 3520

$B \simeq 5$ kG	$U_m \simeq 8$ kJ
$\ell \simeq 50$ cm	$U_p \ll U_m$
$n_e \simeq 1.4 \times 10^{15}$ cm^{-3}	$M \simeq 2$ mg (carbon, oxygen)
$v \simeq 10$ cm/μs	$U_\kappa \simeq 10$ kJ

where:

B = peak ring magnetic field	U_m, U_p, U_κ = ring magnetic, thermal, and directed kinetic energy
ℓ = full-width-half-maximum ring length from magnetic probes	M = ring mass
v = ring velocity at impact plate	

Figure 3 shows the signal observed on the unfiltered XRD. The output power of the compact torus is approximately proportional to the XRD voltage with a peak output power of 280 MW for a XRD signal of 8 volts. There are factor of ~2 uncertainties in relating the XRD voltage to the total radiated power from the ring. Since we did not have spectral data, we cannot account for the varying response of the XRD with photon energy, so we have simply used 0.5* peak response (from the tabulated response data) which is reasonably accurate if most of the emitted radiation is in the range 10-40 eV. If large amounts of energy are at photon energies > 40 eV then the scale factor can substantially underestimate the radiated power. The other largest uncertainty is the total ring volume (>> volume sampled by the detector). For the calculated scale factor the total radiating volume of ring plasma is taken to be one half the volume before stagnation as expected from shock wave theory.

Note the "foot" on the radiation pulse at > 70 MW is roughly the magnitude expected from the balance of Ohmic heating with radiation in the torus before impact, and is consistent with the magnitude of the radiated power observed on the VUV detectors upstream of the impact plate.

Table 2 shows the total observed fluence (given the uncertainties stated above) and compares it with the predicted output for an analytic theory of shock-heating, electron-ion coupling and radiation (see Ref. 2), and a LASNEX simulation performed by Maggie Gee of the LLNL Physics Department. For the 1D LASNEX run, the parameters were chosen to model the ring properities given in Table 1 with the assumption of a pure Carbon plasma.

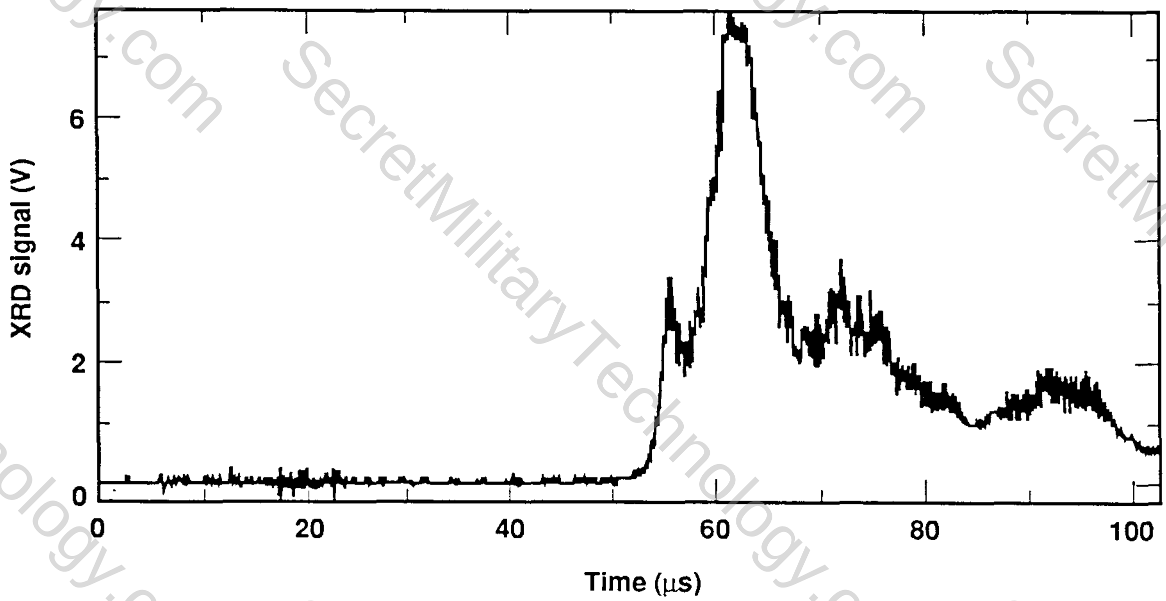

Fig. 3. Bare XRD signal on shot # 3520

Table 2

Analytic X-ray Output Theory	LASNEX	Observation Shot #3520
$\ell_{shocked} = 25$ cm	$\ell_{shocked} \cong 21$ cm	-
$U_{p_{shocked}} = 5$ kJ	-	-
$U_{RAD} = 1.8$ kJ	$U_{RAD} = 4.1$ kJ	$U_{RAD} = 2.7$ kJ ($\ell = 25$ cm assumed)
$\tau_{RAD} = \frac{\ell_o}{v} = 5$ μs	$\tau_{RAD} = 3$ μs	$\tau_{RAD} \cong 7$ μs
$h\nu \simeq T_e = 40$ eV	$h\nu_{peak} = 35$ eV	$h\nu > 10$ eV

The spectrum predicted by LASNEX is shown in Fig. 4. The observations while somewhat preliminary, are thus consistent with the expectations from a simple theoretical model as well as the LASNEX code. We intend to repeat these experiments in the near future with a larger complement of x-ray/VUV diagnostics in the stagnation region, including a grazing incidence spectrograph to characterize the spectrum.

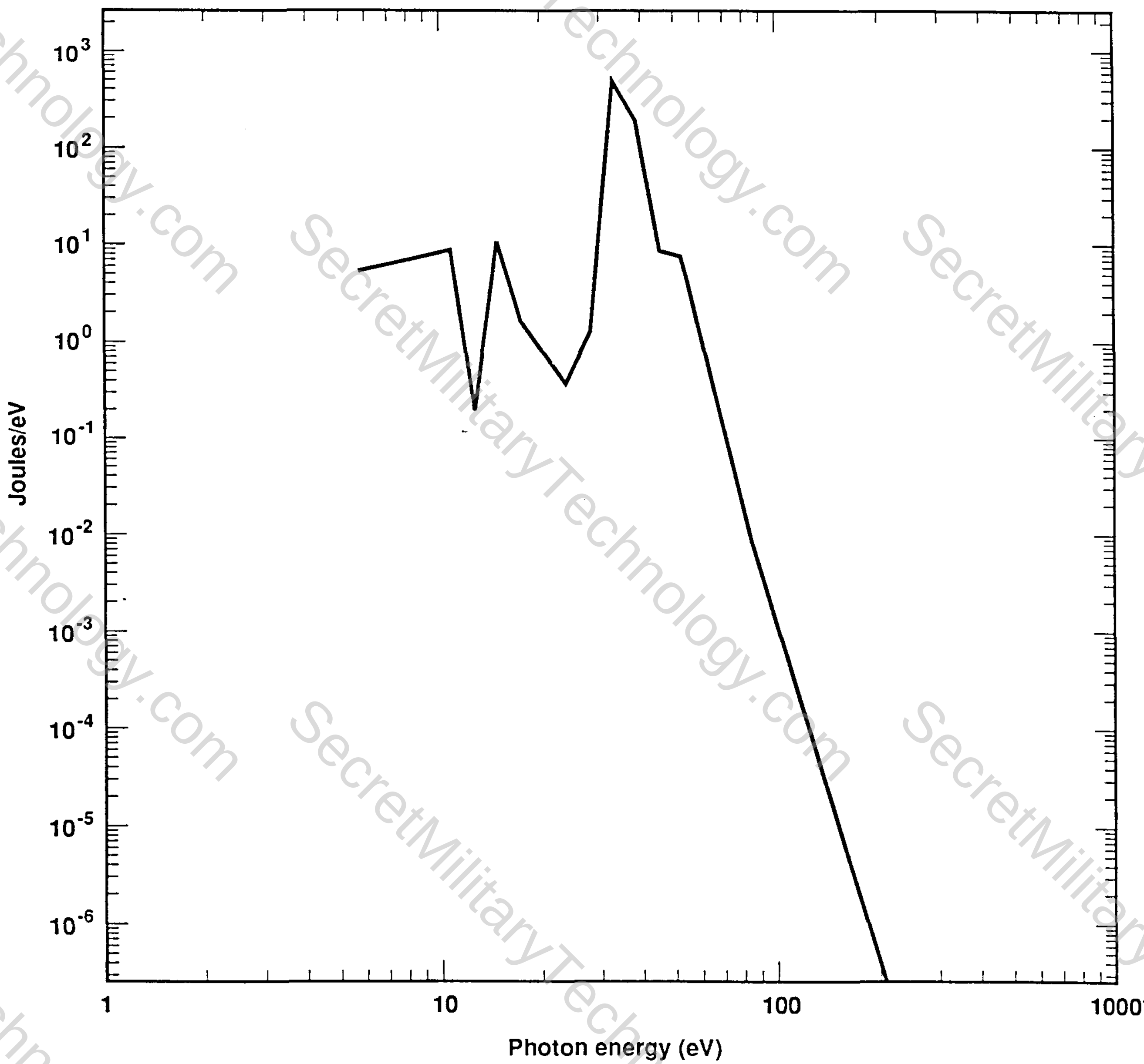

Fig. 4. LASNEX predicted spectrum for the compact torus parameters of shot #3520

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