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Ref: 14-F-1419

Mr. John Greenewald
The Black Vault
[redacted]

Dear Mr. Greenewald:

This responds to your enclosed Freedom of Information Act (FOIA) request, submitted on September 11, 2014. Your request was received in this office that same day, and assigned case number 14-F-1419. We ask that you use this number when referring to your request.

The Defense Advanced Research Projects Agency (DARPA), a component of the Office of the Secretary of Defense, conducted a search of their records systems and provided the enclosed records, totaling 69 pages, determined to be responsive to your request. These records are appropriate for release in their entirety, without excision.

This constitutes a full grant of your request, and closes your case file in this office. There are no assessable fees associated with this response.

I trust that this information fully satisfies your request. If you need further assistance or would like to discuss any aspect of your request, please do not hesitate to contact the Action Officer assigned to your request, Ms. Corynne Gerow at corynne.n.gerow.civ@mail.mil or (571) 372-0410.

Sincerely,

Stephanie L. Carr
Chief

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7E20 Strategic Technology

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June 1977

# Electron Beam Systems in Space (U)

Robert M. Salter, Jr.

A Report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY



DecIAss:fied by:
Mark Boyd
Director, SID

DecIAss:fied on:
January 26, 2015



Rand
SANTA MONICA, CA. 90406

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Mark Boyd
Director, SID
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PREFACE

U ~~(S)~~ The "Electro-ring" concept of using electron rings in space for energy storage originated with the author during Rand studies of radiation (laser, particle beam) weapon systems in space. The requirement for large energy sources in space to support military radiation systems is evident from this work, as reported in R-1802-ARPA, *Electron Rings in Space for Energy Storage* (U), and other Rand studies on space-based weapon systems.

U ~~(S)~~ The space systems considered here have been examined on an exploratory basis only. The research has focused on applications, under the tacit assumption that the formulated electron beam ("e-beam") concepts will be feasible. The author identifies various concepts and discusses their potential mechanization on a broad basis. The level of effort was not sufficient for a rigorous pursuit of the physics and engineering of the systems. Known physical effects have been factored in as performance constraints; however, many unknowns exist, particularly in the area of electron beam stability. Additional effort is required to resolve technical questions more precisely; project support to date has not permitted such in-depth resolution. Both theoretical investigations and in-orbit experimentation will be needed to determine the future prospects of electron beam weapons and Electro-ring energy storage devices.

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## SUMMARY

U ~~(S)~~ Electron beams are examined for potential use as space radiation weapons, active/semi-active sensors, energy storage and transfer mechanisms, and communications media. Use of 7 GeV electrons as a weapon against in-space reentry warheads is investigated with a mission labeled "SPEAR." Prospective methods for generating such electrons are considered. Analogous use of proton beams is briefly reviewed.

U ~~(S)~~ Future high-power lasers and particle beam systems will require space-borne energy supplies of $10^{11}$ - $10^{13}$ J. Such energy must be readily convertible to high power for beam weapons, radars, and similar uses. Storage by means of electron kinetic energy in a storage ring appears to be a prospect for meeting this objective at a reasonable weight compatible with space systems support. (Pulsed nuclear devices have been proposed for space power, but lightweight mechanization of this concept has not been formulated.) A chemical laser, for example, would require 500 to 50,000 tons of fuel for the above energies.

U ~~(C)~~ A potential energy storage system composed of an electron ring coupled to a nuclear SNAP unit (the "Electro-ring") is examined. Energy regimes permitted, ring configurations and correctional devices within the constraints of known physical effects are studied. Direct use of Electro-ring electrons and electrical conversion is compared for payloads such as lasers and weapon electron accelerators. A low-divergence photon beam laser substitute of synchrotron radiation produced from Electro-ring electrons is investigated.

U ~~(S)~~ A SPEAR weapon system using a single-ring version of an Electro-ring for $10^{12}$ J of energy storage requires ring electron energies of 275 MeV; a 32 kW accelerator provides the electron fluence required for filling the ring in a year. Four equally spaced equatorial SPEAR satellites on circular orbits at 3000 miles altitude are assumed for a useful anti-RV coverage pattern at 27° to 48° latitudes. (A similar array at 7000 miles can extend coverage to 64° latitude.) In-space detection and kill are assumed. Comparison is made with broader coverage but less effective high-power, short-pulse visible-light lasers.


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Use of the Electro-ring's SNAP system to arc-heat hydrogen for propulsion of shuttle loads to high altitude is explored.

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CONTENTS

GLOSSARY

| | |
|---|---|
| AI | Atomics International |
| ASAT | Anti-satellite |
| B | Magnetic field intensity |
| BPI | Boost phase intercept |
| CEP | Circular error of probability |
| CP | Charged particle |
| CPB | Charged particle beam |
| cylac | Cyclic linear accelerator |
| DE | Directed energy |
| DSP | Defense Surveillance Program |
| E | (Relativistic) electron particle energy |
| ERDA | Energy Research and Development Administration |
| $Fe^{(t)}$ | Fractional space-charged neutralization |
| FFAG | Fixed field alternating gradient |
| G | Gauss |
| GeV | Giga electron volts |
| H | Magnetic field |
| i | Current |
| $i_\ell$ | Limiting current |
| $i_\alpha$ | Alfvén current |
| ICBM | Intercontinental ballistic missile |
| IR | Infrared |
| J | Joules |
| kA | Kilo Amperes |
| kG | Kilo gauss |
| kW | Kilowatts |
| kWe | Kilowatts (electric) |
| L | Length |
| LAMPF | Los Alamos Proton Accelerator |
| LASL | Los Alamos Scientific Laboratory |
| LBL | Lawrence Berkeley Laboratory |
| linac | Linear accelerator |

| | |
|---|---|
| LLL | Lawrence Livermore Laboratory |
| LOS | Line-of-sight |
| m | Electron rest mass |
| ma | Milliamperes |
| MeV | Mega electron volts |
| MHD | Magnetohydrodynamics |
| MHz | Megahertz |
| MJ | Mega Joules |
| MKS | Meter-kilogram-second (system of units) |
| MUSL-2 | Designation of a University of Illinois accelerator |
| $n_i$ | Number of ions per unit volume |
| nm | Nautical mile |
| OK | Optical klystron |
| R | Radius of ring |
| rf | Radio frequency |
| RV | Reentry vehicle |
| SLBM | Surface-launched ballistic missile |
| SNAP | Space nuclear auxiliary power |
| SPEAR | Space Projected Electrons Against Reentry Vehicles |
| SRI | Stanford Research Institute |
| uv | Ultraviolet |
| W | Weight |
| X | Horizontal distance |
| XeO | Xenon oxygen |
| ZI | Zone of interior |

## I. INTRODUCTION

U Theoretical[1] and limited experimental[2] investigations have indicated the possibility for propagation of electrons (and other charged particles) in outer space by means of the principle of space-charge neutralization. Theory anticipates that ions in space will provide for partial neutralization of transiting relativistic electron beams, perhaps permitting them to maintain an equilibrium collimation over long distances. The ability of an electron beam to propagate without divergence due to instabilities or other factors is yet to be demonstrated. This subject will be considered further at the end of this section. If space-charge-neutralized propagation of electrons can be achieved, useful missions can be performed with electron beams in space. But this report does not mean to imply that this is a definite possibility.

U This report deals with two applications in space, both depending upon this space-charge-focused mode of propagation. Rand has studied the use of electrons in directed energy (DE) weapon (and other) beams under Air Force sponsorship. The Electro-ring application of electron beams to energy storage rings was investigated under ARPA auspices.[3] Neither use is critically dependent upon the other, but they are mutually supporting.

U In general, long-distance applications of electron beams will require multi-GeV particle energies for weapons, communication, radar, and other purposes. At shorter ranges, correspondingly lower electron energies can be considered, except, perhaps, where penetration of hard targets is required. Even electrons of a few MeV might be used (in a drift mode) for certain communication and sensing roles.

U Electron energies (E) for storage rings will depend upon the type of ring configuration, amount of energy stored, and altitude. Current-limiting effects rule out $10^{11}$ J single rings at much below E = 75 MeV,* although use of a helical configuration may permit particle

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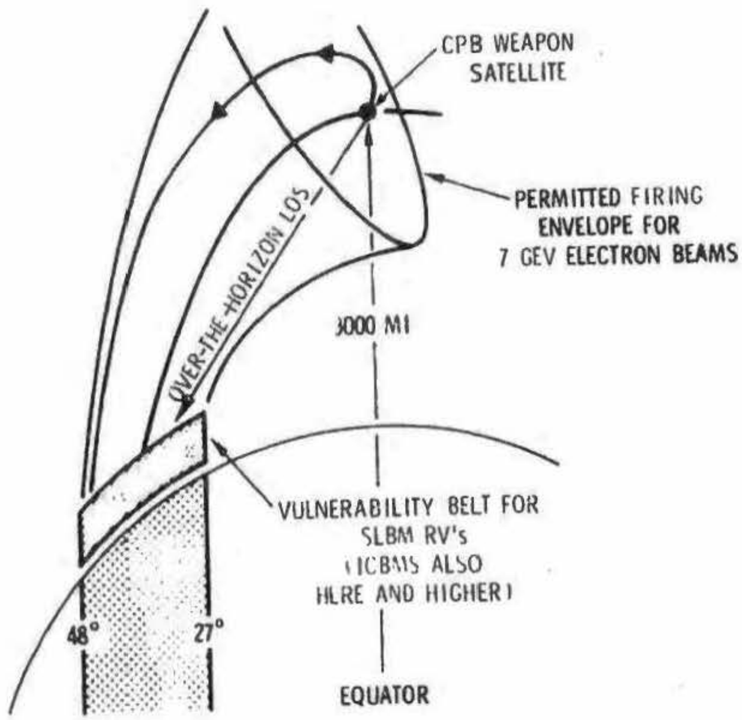
*(U) Cases studied at geosynchronous orbit altitude indicate an $E_{min}$ permitted of 28 MeV. However, operation at these higher altitudes involves considerable uncertainty.

energies down to 20 MeV. Single ring electron energies are probably limited to a maximum of 500 MeV because of beam handling losses. However, rings propagating around the world at the equator are a (distant) possibility, and these would use electron energies at a GeV or more. See Ref. (3) for further discussion.

U There is considerable overlap in electron energies between weapon (and other) directed-energy beam applications and electron rings for energy storage, indicating that electrons from a storage ring might often be applied directly without conversion (such as in satellite self-defense). The storage ring conversion problem is treated in detail in Ref. (3). Various methods are considered for generating electricity from the (highly relativistic) electrons. Other approaches for directly powering user devices include transformer-like conversion for electron accelerators, optical klystron amplification of laser radiation by direct interaction with ring electrons, similar interactions to generate laser light directly in the free-electron laser, and ring-electron-produced synchrotron radiation to form a low-divergence optical beam.

U The design example discussed in this report in detail is a case in which the directed energy electron beam system is strongly supported by the electron ring energy store. The mission selected is 7 GeV electron beam in-space destruction of ballistic missile reentry vehicle (RV) systems. This is called the "SPEAR" weapon system (an acronym for Space Projected Electrons Against RVs). In support of SPEAR, a space-borne Electro-ring power supply system is assumed with a storage of $10^{12}$ J in an electron ring of 275 MeV electrons.

U Four equally spaced SPEAR satellites on equatorial, circular 3000 mile orbits are assumed to cover latitude belts of 27° to 48° (see Fig. 1). Additional SPEAR satellites at 7000 miles can cover the 48° to 64° latitude bands. The e-beam ring power systems at these two altitudes are estimated to weigh 30,000 lb and 25,000 lb, respectively, although the weight advantage at the higher altitude is very nearly offset by lowered payload capability of rocket booster systems. Each SPEAR satellite is estimated to be capable of handling 12,000 targets, seeking out and applying 10 MJ pulses to each target at a rate of one per second.




~~(S)~~ Fig. 1 — SPEAR (Space-Projected Electron Against Re-entry vehicles) S)

U ~~(S)~~ In the multi-GeV range, protons offer no particular advantage over electrons as a weapon beam.* Proton target kill effectiveness is somewhat better. However, with present machine technology, protons are more difficult to generate than are electrons. Perhaps the collective accelerator approach (still a largely unknown field) may alleviate this situation. A collective accelerator would be of particular interest if it were to require electrons of the same energy as the storage ring; in the cases considered, these energy levels were widely different.

U ~~(S)~~ Laser beams propagated at distances comparable to SPEAR would be greatly spread out (many feet for a 1 μrad beam, which is about the best divergence that currently can be projected for a high-power weapon laser). Effectiveness against RVs would be nil, but softer targets might well be countered. Collection and re-focusing of a laser beam by a distant satellite that is near the target is one way around the laser divergence problem but is considered to be extremely difficult to manage in a military operational sense.

U ~~(S)~~ Neutral beams under consideration would have (at best) divergence levels comparable to weapon laser beams. The neutral beam's target kill mechanism would be better than that of a laser; but even so, because of beam divergence, a SPEAR-like mission would require hundreds of space weapon platforms. Existing neutral beam concepts are based upon ion acceleration and aiming, followed by particle charge-conversion to the neutral state. Neutral beams thus, at present, have acceleration limitations similar to those of protons and other ions.

U ~~(S)~~ Electron storage ring cases were studied for geosynchronous altitudes, but it is extremely uncertain that such a ring could be sustained, especially in view of solar wind effects on magnetic field lines in this regime. However, with ion density and earth's field levels believed to exist at 22,250 miles, compatible ring cases were found. For example, the current-limiting electron energy for a $10^{12}$ J store is 59 MeV at geosynchronous altitudes (it is 162 MeV for 7000-mile and 275 MeV for 3000-mile altitudes). If the volume of space influenced by the ring must be increased by a decade beyond where ring energy equals the

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*U ~~(S)~~ The prospects for propagation of protons through space assuming space-charge neutralization are discussed in Sec. IV.

energy of the earth's magnetic field enclosed by the ring,* then electron particle energies of 145 MeV are specified. This conservative example still indicates a possible power system weight of 32,400 lb with a 1000 ft long correction magnet. Reduction of magnet length to a more manageable 250 ft would increase the power system weight perhaps to 40,000 lb.

(U) Political, military countermeasure, electromagnetic communication spectrum pollution and safety aspects of long-term, high-energy electron storage rings in space need further scrutiny. These problems would be particularly acute for geosynchronous orbits because of the large size of rings and the considerable number of other user systems in this region.

U ~~(C)~~ The physics of the space-charge-focusing propagation process is considered specifically in Sec. IV. However, the status and limits of our knowledge of the physical principles involved are the key to the application of electron beams in space. There is no guarantee at this time that charged-particle beams can be stably projected into ionospheric regions by means of the charge-neutralization mechanism suggested or that they will maintain collimation over a large range. The theory examined to date has shown that if a high-quality accelerated beam of electrons is subjected to partial charge neutralization such as might be supplied by positive space ions, then the calculated balance of forces within the beam would provide for equilibrium collimation. Laboratory experiments have demonstrated over very short ranges this so-called space-charge focusing effect both for steady-state and for transient changes of the neutralizing ion density. Calculations of multiple scattering indicate that at space particle density levels, scattering effects should have negligible effects on e-beam divergence over large distances.(1)

U ~~(C)~~ The above conditions are necessary but not sufficient to assure that collimated e-beams can be transmitted through space. Subtle phenomena such as those attending the neutralization process (i.e., ion-dragging or "collective acceleration" effects), the ever-present

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*(U) Assuming a square cylinder regime of influence.

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bias of earth's magnetic field, or coherent fluctuations in space particle or magnetic field distributions might well give rise to beam instabilities and increasing divergence.

U Additional unknowns are introduced in the storage ring applications. Certainly here there will be increased concern over the possibility of collective acceleration of ions that are subjected to the passing e-beam over protracted time periods. Also, continuous recirculation of the storage ring electrons through satellite beam handling equipment will invite the many sources of beam instabilities encountered in laboratory storage rings and cyclic accelerators. Another unknown peculiar to the storage ring application is the extent to which the earth's magnetic field can constrain a high energy Electro-ring and the potential consequences when energy storage levels become commensurate with the energy of that portion of the earth's field providing ring constraint.

U As will be seen in Sec. IV, the degree of uncertainty is perhaps even greater in the case of the space-charge focusing of proton beams in space than with electrons.

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## II. RECOMMENDATIONS

(U) Review of existing intelligence data collections as well as new investigations of foreign intelligence should be conducted in light of the unique concepts described herein.

U ~~(C)~~ The effects of electron beam weapons and energy storage rings on future military operations should be analyzed to assess the value of these systems. This can be performed before their feasibility determination by assuming that such systems will be successful and using the maximum performance that would be permitted by known physical and practical engineering limitations. These analyses should be conducted in context with future space warfare scenarios. (Present existence of comparable scenarios is not known.)

U ~~(C)~~ Steps should be taken to affirm or deny feasibility of the electron directed energy (DE) propagation and storage ring concepts assumed here. A primary area of concern at this time is that of beam stability in the storage ring configuration. Theoretical analyses should be performed as soon as possible to determine possible negative results. (Positive theoretical confirmation cannot be relied upon but must await future experimental demonstration.) An experimental program initially of simple space beam propagation, followed by later phases involving recirculating beams and servoed beam handling systems should be mounted.

U ~~(C)~~ A development plan for electron beams should be prepared that properly organizes the above-recommended steps and also provides for long-range development of critical components and system requirements. Identification of systems requiring long lead-time development and determination of R&D decision and "choke" points (critical path elements) are a fundamental part of this process.

## III. SYSTEM CONCEPT

(U) Detailed treatment of the system selected as a reference for illustration of the potential application of electron beams in space will be found in Ref. (3).

U The mission chosen for purposes of example is one of detecting and destroying nuclear warhead RVs during their midcourse trajectory phase (the SPEAR mission). For this purpose, an array of four satellites equally spaced around the equator in 3000-mile high, circular orbits is assumed. Each satellite contains a complete electron beam weapon system using 7 GeV electrons both as sensor probes and for weapon kill. The mission arrangement of the SPEAR system is shown in Fig. 1.

U Hostile ballistic missiles--both SLBMs and ICBMs--are detected optically by passive sensors during launch and are subsequently tracked during and after vernier cutoff. This function will be performed by the SPEAR satellites, by other space systems (such as DSP), and by ground systems. Nearly all SLBM launches and many ICBM launches will be in view of SPEAR satellites.*

U The SPEAR concept is based upon in-space destruction of RVs above 180 miles altitude. Studies have been performed at Rand[4] and elsewhere[5] for radiation weapon interception of ballistic missiles during boost phase (BPI). Possible BPI modes are discussed later in this report. Requirements for projection of electron weapon beams in the lower atmosphere are quite different from (and much more difficult than) those in space. This problem is discussed in Ref. (2).

U The key to propagation of electron beams in space lies in the space-charge focusing principle (which is covered in detail in Sec. IV). This principle may permit the projection of highly collimated charged-particle beams over long distances. In this respect an electron beam portends to be superior to a laser beam. For example, a laser beam

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* U If a second array of SPEAR satellites is placed at 7000 miles, the LOS horizon is increased (from 55° latitude) to 69° latitude; thus, most ICBM launching sites would be included in view as well.

with a microradian divergence will be 25 ft in diameter at 5000 miles, whereas a highly relativistic electron beam might be less than an inch in size.(1)

U ~~(S)~~ Also, weapon particle beams (both charged and neutral) are designed to penetrate the target and to destroy it by energy placed within the structure. A laser beam does not have this property and must rely on damage mechanisms from surface-induced effects.

U ~~(S)~~ Laser beams are not affected by the earth's magnetic field; electrons and other charged particles are. Figure 1 illustrates the permitted firing envelope for a 7 GeV electron weapon beam projected from a 3000 mile equatorial satellite. Although the general mode is to fire along field lines, the higher energy of the particles permit firing at an angle to the lines, which allows coverage from 27° to 48° latitude.

U ~~(S)~~ The SPEAR mechanism for RV acquisition and kill assumes the use of perhaps $10^7$ micropulses of electrons in barrage fashion to ferret out precise target location, followed by more intensive electron pulses directed at the RV for kill purposes.* The barrage concept for RV target acquisition was originally developed by Lyons and Bussard for strategic weapon laser systems.(6) Pointing and tracking of the e-beam is a major problem area.

U ~~(S)~~ In more detail, the target acquisition procedure is as follows. The RV is located optically to a CEP of about a kilometer. The electron beam (which of course does not follow line-of-sight) is aimed to intercept this region of space based upon the calibrated and predicted direction and strength of the earth's magnetic field in the region of the electron trajectory. Each precursor micropulse fired is correlated in time and is associated with a particular set of beam aiming coordinates. Back-scattered radiation or characteristic rf signals emanating from the RV denote a "hit" by a precursor pulse registered

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* ~~(S)~~ U Theoretical concepts for electron propagation in space by space-charge focusing place no restriction on the size of the pulse. This differs from electron beam requirements in the lower atmosphere, where long pulses and instantaneous powers of $10^{13}$W are needed for atmospheric hole-boring to create a low-density channel for electron propagation.

in time.* The beam aiming region is then narrowed down to the proper coordinates, and beam intensity is stepped up to the "kill" level.

U This process occupies about one second per RV, with a $10^7$ J destruct pulse being delivered in the last 150 msec.† Flight times of SLBM RVs in space will be about 20 minutes; in such a time period, one SPEAR satellite might handle 1200 targets. To do so, however, would require about $1.5 \times 10^{10}$ J output (or perhaps $10^{11}$ J of input) energy.

U A critical need in such a space weapon system is for a large store of energy readily convertible into high power. A second use for electron beams would be to create an energy storage ring in space.(3)

U Figure 2 illustrates such a storage ring schematically. Electrons are generated in an electron accelerator, focused, and projected into space transverse to magnetic field lines. Bending in the earth's field will tend to form a ring of electrons. A beam handling servo system in the satellite assures that the direction of electron projection causes the electrons to be appropriately returned to the satellite by the earth's field.

U A fairly low-power accelerator, energized by a nuclear (or perhaps a solar) unit, is assumed to build up the store of ring electrons over a long period. Additional energy must also be supplied to make up ring losses over this same period. When needed, electrons are extracted from the ring beam and applied to a conversion system feeding a weapon accelerator, laser, or other power user.

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*(U) The scattered radiation might be sensed by the SPEAR vehicle itself, but this function could also be enhanced by orbiting swarms of sensing "transponder" packages to pick up signals in a region near the target. U

† It is assumed that through optical tracking the target RV's velocity vector is determined to the extent that the SPEAR beam aiming system can be properly slewed to accommodate the several hundreds of meters traveled by the target in 150 msec. Vehicle/beam stabilization and control requirements for hitting the target should also be adequate to provide this slewing function. The alternative is to buffer the output pulse in the outer track of the acceleration to reduce pulse time by a factor of $10^3$, but synchrotron losses over a period of 150 msec would be severe at 7 GeV electron energy.

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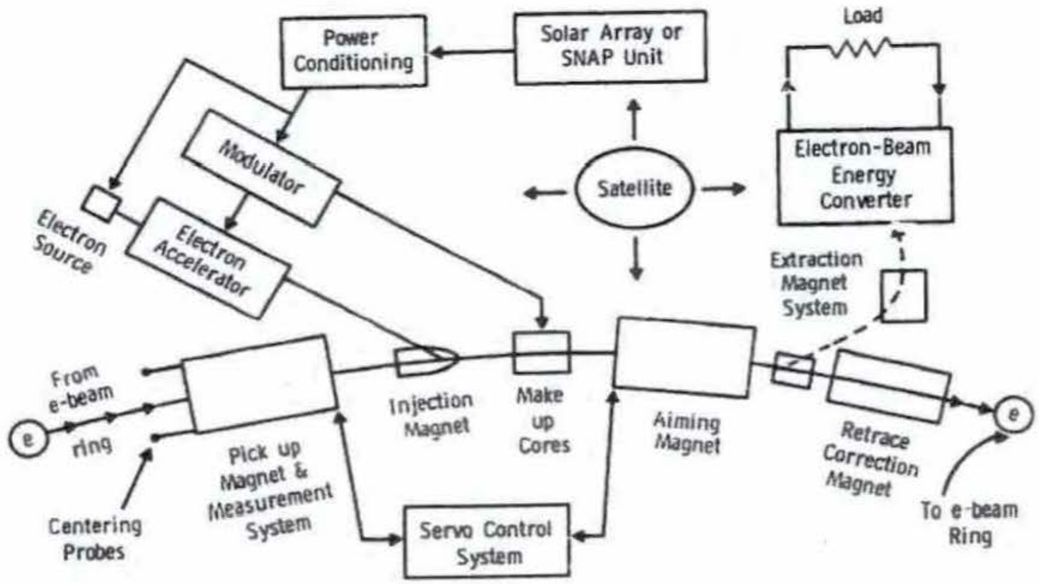


U ~~(C)~~ Fig. 2 — Satellite-borne electron ring beam-handling and supply system (U)



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U ~~(S)~~ The example case selected here assumes $10^{12}$ J of Electro-ring storage, which is a decade higher than required for the 1200 RV "kills" in the above discussion. A 32 kW accelerator is calculated to supply the (275 MeV) electrons needed to build up to $10^{12}$ J of energy over a year's time. Additional power of about 27 kW is required to overcome ring synchrotron losses (toward the end of the year's period). A small fraction of this second power increment is needed to restore inherent synchrotron losses due to ring bending, but the bulk is applied to replace energy lost in the beam handing system in continually correcting electron direction due to earth's field gradient effects.

U ~~(S)~~ A nuclear power "SNAP" system is assumed of $\sim$59 kW. The total weight of payload at 3000 miles (from a single shuttle load to low orbit) is found to be 45,000 lb, of which 30,000 lb is taken up with the $10^{12}$ J electron ring store system.* The remaining 15,000 lb might possibly be adequate for a weapon accelerator system (and more probably enough for a weapon laser payload). The 7 GeV electron accelerator assumed for weapon purposes is a "colliding-beam" Cylac type, which takes advantage of space-charge focusing to obviate the need for heavy focusing magnets. In the event that greater weight is needed, two (or more) shuttle loads, each with a 50 kW SNAP system, could be considered. The total payload weight with two shuttles then available to the SPEAR accelerator system would be $\sim$55,000 lb (15,000 lb in one vehicle and 40,000 lb in the other).

U ~~(S)~~ If higher-latitude SPEAR coverage is desired, a second array of equatorial satellites at 7000 miles altitude would extend the coverage pattern from about 48° to 64° latitude to at least include most of the ground-launched strategic missiles. A $10^{12}$ J storage ring at 7000 miles equatorial can be achieved with somewhat lower electron energies (162 MeV vs 275 MeV required at 3000 mi). The resultant payload weight saving (due primarily to a lower value of E and thus reduced electron accelerator weight) of 5000 lb is nearly offset by the 4000 lb reduction in payload carrying capability to the higher altitude.

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*(U) The SNAP engine is assumed to boost to the higher orbit level by electrically (arc) heating a hydrogen propellant. Items constituting the 30,000 lb energy storage system are listed later in Table 1.

U ~~(S)~~ The example case is based on an anti-RV electron beam system. In the altitude range assumed, alternative applications of electron beams for ASAT missions or for radar, inspection, super-hard communications, or power transfer can be considered. Even the storage ring electrons at 150 to 275 MeV can be directly used in some applications, such as for satellite self-defense.

U ~~(S)~~ In Ref. (3) many other mission uses are discussed, for instance weapon lasers. At several thousand miles range, even a highly focused laser beam has a spot size of many feet in diameter, which renders such a beam inadequate against RVs. However, this energy density level might be adequate for disablement (such as blinding) or even kill of fairly soft space targets. Relay of laser beams generated on a SPEAR satellite by high-latitude mirror-bearing vehicles might also be possible, although the mechanization of such a scheme is intricate.* Laser beams can also be used in radar sensing, communications, and power transfer.(7)

U ~~(S)~~ Methods for directly generating laser beams from storage ring electrons are treated in Ref. (3) along with a discussion of a Rand-conceived use of synchrotron radiation directly from storage ring electrons. With the aid of anamorphic secondary optics and a technique for producing a small synchrotron-radiation source size, it was found that beam divergences competitive with those of high-power lasers theoretically could be achieved. Very few of the laser applications studied make direct use of the laser's properties of coherence and monochromaticity and thus synchro-beam substitution can be considered.

U ~~(S)~~ Following is a brief review of possible proton beam systems. A 7 GeV proton weapon beam would enjoy about the same magnitude (although opposite direction) of bending in the earth's magnetic field as a 7 GeV electron. The Cylac accelerator assumed for electrons cannot be applied to protons of this energy. A collective proton accelerator

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*U ~~(S)~~ Both research is being performed on space-mirror-redirected laser beams emanating from ground sources. The space-to-space arrangement at least would avoid atmospheric effects.

(U) A physical model for in-space proton propagation analogous to electron space-charge focusing is presented in Sec. IV.

conceivably could be directly driven by a space electron storage ring. However, electron particle energies required for $10^{11}$ to $10^{13}$ J rings are far too high for this purpose. Perhaps a two-stage arrangement could be effected whereby high-energy Electro-ring electrons are converted into lower energy electrons and a second, buffer type of electron storage ring then created to feed the collective accelerator.

U Protons would not be candidates for energy storage rings in space except for earth-circling configurations. If this latter type of ring were to be found workable, then multi-GeV protons or electrons could be stored over a long period of time using low-power accelerators; these particles then could be directly extracted and aimed for SPEAR and other long-range propagation purposes.

U Very rough estimates of space component systems arrangements and weights are used in this report to provide a feeling for the usefulness of electron DE and storage ring systems. The "rubberized" weight values for space power tradeoff studies were primarily developed to provide for comparison of performance options, and absolute weight levels may be quite inaccurate. However, since this report compares 25,000 *lt* space power systems with equivalent 5000 *ton* conventional energy sources such as laser fuel or chemical power, there is considerable latitude for error without modifying the conclusions drawn.

# IV. BEAM PHYSICS

(U) Physical principles significantly affecting electron beam systems applications in space are enumerated and discussed below. There may well be other criteria undetermined at this time--particularly stemming from beam dynamical stability considerations--that will bear heavily on system design and performance. It is not at all certain from present theory and experiment that electron beams can be usefully propagated in space, or that high-energy storage rings can be properly constrained by the earth's magnetic field.

## SPACE-CHARGE NEUTRALIZATION

U ~~(S)~~ Electron beam use in space is based upon the precept that such beams can maintain collimation while propagating through space by means of space-charge neutralization (or so-called space-charge focusing). A beam containing electrons will tend to diverge rapidly (or blow up) because of electrostatic repulsive (coulombic) forces between the electrons. In a highly relativistic beam, another force tends to offset the coulombic repulsion--a radially inward force due to magnetic self-fields, which in turn are derived from the high-intensity electrical current represented by the electron beam. In such a relativistic beam, the magnetic self-forces very nearly counterbalance the coulomb repulsive forces. This force difference is proportional to $1/\gamma^2$ where $\gamma$ is a relativistic parameter equal to relativistic energy $\div$ particle rest mass.

(U) As an example, electrons have a rest mass (measured in energy units) of .511 MeV. Thus 5 MeV electron is quite relativistic and has a $\gamma$ of $\approx 10$. From the above it is seen that the opposing radial forces differ by $1/10^2$, or 1 percent. Thus, if the coulomb forces can be reduced by 1 percent, the beam forces in a 5 MeV electron beam will be placed in equilibrium.

U ~~(S)~~ In space there is a source of ambient ions that could potentially neutralize part of the electrostatic charge in an electron beam.[1] The mechanism conceived is that a collimated electron beam propagating in space will expand or contract to that equilibrium diameter where the beam encompasses the particular number of ions that provide the proper neutralizing (positive) charge. Terrestrial experiments have demonstrated this phenomenon over distances of tens of feet and have shown that a spatial change in plasma ion density will induce the expansion or contraction of the beam indicated by theory.[2]

(U) It is assumed that an electron beam transiting an ionospheric region will eject ambient electrons (as these are at low energy and are highly mobile), while ambient ions, because of their larger mass, are fairly immobile and will remain fixed in position as an electron beam passes by. (Some degree of capture and collective acceleration of ions is probably to be expected, however.) This concept applies to a short pulse of electrons on a one-pass basis. Possible effects of a long pulse of electrons, or even more particularly of a closed circuit of electrons such as in a storage ring, may substantially override this concept.

U ~~(S)~~ This space-charge-neutralization focusing principle can be assumed to be used for propagating beams from point to point through space and also can be applied to space-borne electron accelerators and to recirculating electron rings for energy storage purposes.

U ~~(S)~~ The theory for space-charge neutralization of protons is symmetrical with that of electrons, although the physical mechanism for neutralization is different. Beam protons are expected to attract electrons from the surrounding plasma as they transit space. In contrast with the electron case (where the neutralizing particles were almost stationary relative to the beam motion) the neutralizing particles (i.e., electrons) for the proton beam will probably tend to be captured by the beam. The neutralizing charge would thus tend to build with time (and as the beam becomes more neutralized it might be expected that the beam diameter would decrease in size). However, since the captured electrons are propagating with the proton beam, although their contributed electrostatic charge reduces the radial coulomb repulsive forces, their contributed electron current also weakens the protons' offsetting magnetic forces.

(U) It is believed that the proton beam would become increasingly more neutral (or would approximate a heavier ion beam). The number of ambient electrons contributing to proton charge neutralization that are not also entrained by the proton beam may be a very small fraction of the total, in which case space-charge focusing of protons may be in question even on a first-order basis (let alone the subtle, long-term perturbational aspects considered as a possible e-beam problem).

(U) This electron availability problem could be viewed during initial phases of proton propagation as if the density of ambient electrons is much less than the corresponding density of positive ions. A proton beam at the same energy and ambient charged-particle density as an electron beam will be 43 times larger in diameter than this corresponding electron beam because of the rest mass ratio of the two particles (i.e., the proton $\gamma$ is about 1/1832 times as large as that of the electron) if both are at relativistic energies. If the effectiveness factor for use of ambient electrons is included, the proton beam may be very diffuse even from the outset.

SPACE-CHARGE-LIMITING CURRENT

(U) A phenomenon encountered in generators of intense electron beams is a current-limiting effect in propagating such an intense beam away from an anode. This limiting current, $i_\ell$, relates the kinetic energy of beam electrons to their electrostatic energy with respect to the anode of the accelerating system. If the actual electron beam current exceeds $i_\ell$, the potential difference to the anode is greater than the kinetic energy of the electrons. When this happens, the beam stops axially and a cathode forms that reflects the beam electrons back toward the anode.

(U) In the general case, beam transport system geometry will modify the magnitude of $i_\ell$. Also if there is substantial ionization of the gas medium through which the beam is propagating, $i_\ell$ can be increased as a time-dependent function of this ionization. The general expression for $i_\ell$ is $17(\gamma^{2/3} - 1)^{3/2} (1 - f_e(t))^{-1}$ G, (kA). In our case, G, the geometrical factor, is essentially unity. Also $f_e(t)$, the fractional ionization, is 1 percent or less. Thus $i_\ell \simeq$

$17(\gamma^{2/3} - 1)^{3/2}$ (kA) is used as the limiting current. Actually, $[(\gamma^{2/3} - 1)^{3/2}]/\gamma$ = .7 at 5 MeV, .93 at 50 MeV, and .985 at 500 MeV so that $i_\ell$ can be approximated by $i_\ell' = 17\gamma$ (kA), particularly since the limit selected is $i_\alpha = i_\ell'/10$ ---arbitrarily keeping an order of magnitude lower to assure that the first-order theory holds for the propagation characteristics predicted.*

U In the cases studied, current limiting effects are of concern only in electron storage rings. A 7 GeV anti-RV SPEAR weapon beam, for example, would probably use milliamperes of beam current rather than an $i_\gamma$ permitted of $2.4 \times 10^7$ amperes.

EARTH'S MAGNETIC FIELD EFFECTS

U The earth's magnetic field has significant effects on electron beam systems. Long-range weapon (or other) beams will demand electron energies at GeV levels to permit sufficient departure from field lines to yield useful propagation "footprints." However, there is an upper limit to electron energies available. As will be noted from experience with existing terrestrial machines, linear accelerators of the GeV variety are quite long. Even a "compact" superconducting type of linac to produce 7 GeV electrons would be over two miles in length. However, recirculating electron accelerators are limited to 6 to 8 GeV because of synchrotron radiation, which increases as $E^4$ where E is the electron particle energy. Since recirculating configurations will probably be the only admissible types of accelerators for generating electrons in space, a 7 GeV limit is assumed for electron weapon beam energy.

U Although the earth's magnetic field effects are a problem for long distance propagation of electrons, they may be beneficial for lower-energy electrons if the space storage ring concept proves useful. A complication is created for storage rings of the earth's field type because of the gradient of the earth's field. Since this field strength decreases radially from the earth's center, a perturbation is introduced

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*(U) A relativistic electron beam, fully neutralized as it leaves the accelerator, would not be attracted by the anode. However, in this case, the (related) Alfvén current limit applies and exerts the same effective limiting value of $17\beta\gamma$ kiloamperes ($\beta$ is essentially unity).

into electron trajectories formed in this field. Such electron orbits do not close on themselves but instead describe an epicyclic motion. To cope with this problem in a storage ring, the satellite's beam handling system must introduce an angular change in electron direction on each circuit of the ring. In Sec. V, the significance of this change will be seen in the "retrace angle correction." For storage rings of interest, losses from this correction are a major factor in system design weight.

Because of their much larger rest mass than electrons, protons will be difficult to use in low particle energy storage rings.* At weapon-beam particle energy levels--i.e., 7 GeV--protons would be bent to about the same degree (although in the opposite direction) by the earth's field. There may be an interesting prospect for an electromagnet proton storage ring at $\sim$10 GeV since protons have inherently lower synchrotron losses than electrons for the same relativistic energy (by a factor of $1.1 \times 10^{13}$), and thus long-term ring storage can be considered for protons. For this reason, a proton weapon beam might be generated by a conventional low-power synchrotron (such as used for the Fermilab Accelerator booster) and stored up over a long period of time (i.e., a year) by such a ring. Unfortunately, the weight of tether required to hold the co-orbiting magnets together against $10^{11}$ J or more of energy becomes too great for useful space applications (although a terrestrial version of this storage ring might well apply).

SPACE ION DENSITY EFFECTS

The useful regime for the space-charge-neutralized propagation extends from about 300 km to high orbit altitudes--perhaps even to geosynchronous.† Below 300 km, ion densities fall off and atmospheric

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*(U) Notwithstanding the potentially less-effective space-charge focusing effects forecast for protons.

† For electron storage rings of the earth's field variety, generally only systems operating in the equatorial plane are considered, although storage rings on satellites of moderately inclined orbits may also be possible. The magnetic field strength does not change appreciably on these inclined orbits, but the field direction does. However, change in ring orientation should be readily accommodated by the satellite's beam handling system.

density increases. Propagation of beams downward from space to ground or lower atmosphere (and vice versa) has been considered and is discussed in other Rand reports.[3] Such propagation modes are not included here.

At high altitudes ion densities fall off, but there may still be useful applications for the resultant beams, particularly at higher particle energies. At the lower altitudes (but above 300 km), ion particle densities $n_I$ of $10^4$ cm$^{-3}$ to $10^5$ cm$^{-3}$ are expected. At geosynchronous altitudes this number may be less than $10^2$ cm$^{-3}$ but is expected to be at least 6 cm$^{-3}$ because of the solar wind. Thus, there may be a factor of $\sim$50 between beam diameters in the lower altitude region and those at geosynchronous altitudes. However, at geosynchronous altitudes, a 1 ma, 7 GeV weapon beam is theoretically predicted to be still only a few centimeters in diameter.

At the lower particle energies and high currents expected for an energy storage ring, and at intermediate orbit altitudes (such as 7000 miles), the equilibrium beam diameters based upon ambient ion densities might be several feet. In these cases, it is postulated that a more ionized environment might be created in the vicinity of the vehicle to reduce beam sizes in the beam handling system.

Potential multiple scattering losses were analyzed by Lauer[1] at 300 km altitudes and found to be negligible for a beam propagating over thousands of miles. This does not guarantee that such losses for a storage ring in this area will also be insignificant over a year's period. However, storage rings of interest are located at 2 decades or more times this altitude, and calculations show reasonable expectations for durations of a year or so. Creation of enhanced ion density in the beam handling area will increase the multiple scattering problem. The region enhanced will have a length of only $1:10^4$ or less of the total electron trajectory, so the integrated effect is expected to be still small. A $10^4:1$ ion enhancement, for example, would cut the duration in half.

SYNCHROTRON RADIATION LOSSES

When a charged particle is deflected in its path by a magnetic (or other field), it radiates energy, $\epsilon \propto E^4/Rm^4$, where R is the radius of curvature of the deflection, E is the particle's relativistic energy, and m is its rest mass. High energy electrons are particularly prone to synchrotron radiation, while protons are negligibly affected by comparison. In the electron storage rings considered here, inherent $\epsilon$ losses from the ring centripetal acceleration itself are small. For example, 100 MeV ring electrons at 3000 mi altitude (equatorial) lose only .1 electron volts/sec because of this source. This is only 3 MeV/year out of 100 MeV. This small loss is brought about through the large radii inherent in earth's field rings (i.e., 41 miles in the case above).

U ~~(C)~~ Beam handling losses can be significant by comparison because of the smaller radii of beam handling magnets. In the above case, a 20 ft long retrace-correction magnet to change beam direction 3° will cause 4.5 times as much loss (as the inherent ring loss). At the higher electron energy levels (say, at 275 MeV) this loss factor becomes 94 rather than 4.5. Parametric representations of these loss variations are given in Ref. (3).

MAGNETIC FIELD ENERGY CONSTRAINTS

U ~~(C)~~ Another area of concern is the energy storage capacity of the earth's magnetic field. This can be measured by comparing the integration of the earth's field energy density over the space region occupied by the electron storage ring with the total energy stored in the ring. The classical electromagnetic energy component of the ring's energy arising from its magnetic dipole field is a small fraction of the total. Also this fraction decreases with increasing electron particle energy.

(U) For electron energies of interest, from a total relativistic energy standpoint, local earth's field magnetic energy capacity seems to be approximately adequate to accommodate the ring. There does appear to be compatibility in comparing earth's magnetic field capacity and the total energy content of the electron ring. However, this is based upon a simple classical model described below.

U ~~(C)~~ The magnetostatic field (H) distribution of a circular current (I) loop of radius R is

$$H = \frac{iR^2}{2(X^2 + R^2)^{3/2}}$$

in MKS units where X is the axial distance. Integrating over this distribution (including nearby tails) shows that it can be approximated by a square cylinder of radius R. On this basis, electron ring energy will equal earth's magnetic field energy for single rings at $10^{11}$ J and 3000 miles altitude in the equatorial plane with electron particle beam energies of 145 MeV. Should lesser electron energies be considered, for the conditions assumed, it is believed that distortion of earth's field lines will occur and that ring sizes may increase somewhat as a result.* Such a change in ring condition will be approximately equivalent to an unperturbed case at some higher altitude so that such changes will still be represented in the parametric distributions studied. In Sec. V this arbitrary magnetic field limitation is shown in graphs of ring performance. It will be seen that the magnetic constraint occurs at about the same particle energy levels as imposed by current-limiting effects.

OTHER PHYSICAL CONSTRAINTS

U Other physical constraints, particularly those stemming from dynamical stability considerations, may have further effects on system design that in turn may affect the feasibility of storage rings or other applications conceived for electrons in space systems. The earth's field storage ring is probably the most critical area of concern on this score. It is well known that cyclic charged particle systems (accelerators and storage rings) are plagued with various forms of beam stability/interaction limitations.[8] In the case of the earth's field ring, perturbations from the surrounding space medium are not expected to affect beam stability significantly. There are, however, incoherent space-charge effects to be considered even in the absence of image forces,[9] although the principal driving function for instabilities is expected to emanate from ring beam interactions with the satellite's

*(U) Other effects may result from this distortion such as Electro-ring instabilities. This phenomenon should be the object of further theoretical and experimental research.

beam handling system. Judicious design could make such interactions a benefit rather than a detriment to ring stability. This aspect will, of course, be the crux of a successful future storage ring development. The actual format of the beam (pulsed or d.c., with or without energy spread, etc.) is expected to be an inherent facet of such system design considerations.

U Another factor that affects system performance and may also affect beam stability is the extent to which positive ions are trapped and dragged along by the beam. To some degree, this effect may be beneficial; but should such trapping occur to a level that is detrimental, the situation may be alleviated through a technique called ion-shaking proposed by Peterson.[10] More detailed discussion of the above phenomena is given in Ref. (3).

U In addition to beam stability effects, there are temporal and spatial variations in the earth's magnetic field (both naturally occurring and possibly man-induced through nuclear bursts) that will affect both storage ring beams and directed energy (DE) beams projected for military weapon systems and other purposes. In general, even the high-frequency components of earth's magnetic field variation have long time constants ($\approx 1$ sec) compared with storage ring systems of interest. Transit times around the largest version of these latter rings are still on the order of milliseconds. Electron beam excursions due to these magnetic field variations are expected to be within the margins of beam handling servo systems, except perhaps in the near vicinity of a nuclear burst.

U Earth's magnetic field variations will also affect CPB weapon beam aiming systems. However, provisions for magnetic field uncertainties are already built into these systems, as will be discussed later. Thus, addition of transitory field uncertainties (as long as these are within system time response capabilities) will not materially change this picture.

U An area of special concern for long-range DE e-beams is the basic mechanism for beam electron scattering of ambient electrons needed to maintain beam collimation through space-charge focusing. Highly simplified calculations of a primitive model of this interaction indicate feasibility, although this is uncertain. There have been, of course, experiments to verify space-charge focusing on a short-range basis,[2] but long-distance application, such as the 5000 mile range of the 7 GeV SPEAR beam, remains to be proved. The model for this latter beam hypothesizes a forward ramp in the beam electron pulse distribution and assumes a pre-pinchdown of the beam before projection into space. It is then postulated that the rate of ambient electron scattering will progressively increase as the pointed nose of the beam penetrates the ionized region because of a progressive increase in the "radial" coulomb field peripheral to the beam. Crude calculations indicate time constants of 10 psec or so for ambient electron movement out of charge influence, which is perhaps reasonably compatible with the minimum-sized pulses considered for SPEAR ($\sim$40 nsec). Since the very point of the pulse nose would tend to flare out with time from retardation effects, there could be a progressive erosion effect on pulse bunching. However, even with a 7 GeV particle energy, bremsstrahlung from beam electrons will propagate at enough higher velocity than the electrons to be a few centimeters ahead of the pulse at midcourse. Since only $1{:}2 \times 10^8$ neutralization is needed, photo-scattering precursor processes on ambient electrons might be adequate to permit leading-edge neutralization of the DE pulse. This is certainly an area for further theoretical and experimental research.

## V. ELECTRO-RING SPACE POWER SYSTEM

[redacted] In the Electro-ring concept, electrons are projected from a satellite vehicle in such a direction that earth's field bending will properly return the electrons to the vehicle's beam handling system. In this way, a recirculating electron ring is formed (as previously noted). Electrons are continuously added to the ring over a long period of time building up to high current and thus energy storage levels.

(U) This section will first consider parametric variation in performance for single storage rings to establish allowable operational regions. Further tradeoffs against tentative, "rubberized" power system component weights are then made to gain insight on typical performance expectations. This is followed by a description of the various elements in the power system and an enumeration of weight factors assumed.

### DESIGN PERFORMANCE TRADEOFFS

[redacted] Both electromagnet and earth's field types of rings are of interest in space storage of energy using electron rings. Earth's field rings can be either single rings (by projecting the electrons exactly perpendicular to the earth's field lines) or a helix formed by projecting the electrons at a slight angle to the perpendicular to the earth's field lines. In the case of the helix, a second space vehicle is (usually) needed to collect the beam and send it back along a field line to the original satellite. Another possible configuration is one where most of the electron bending is done by electromagnets. A typical "ring" of this type would be an 180° magnet located in each of two co-orbiting space vehicles, yielding a long, narrow, "race-track" type of configuration. Because of inherent energy loss due to synchrotron radiation from the circulating electrons, only earth's field types of rings with their large radii are suitable for long-term energy storage.

[redacted] Helical configurations of earth's field rings have the advantage over single rings in that for a particular level of stored energy, the circulating electron current is much lower. This in turn permits use of lower electron particle energies (E). However, single rings are simpler in concept, and if useful solutions can be found, they would be preferred over helical types. Although helix and electromagnet rings are not considered further here, they are discussed in Ref. (3). Also covered in Ref. (3) are single rings circling the earth in the equatorial plane.

[redacted] Because of current-limiting effects, single rings on 3000 mile high equatorial orbits are limited to a minimum electron particle energy of 60 MeV when $10^{11}$ J is stored. Since a further factor of ten limit is imposed on $i_g$, the minimum permitted E is 130 MeV. If $10^{12}$ J is desired, then this minimum is set at 275 MeV. Going to a higher altitude alleviates this situation somewhat (since the lower B field yields a larger ring for a given E, requiring less current for a given total stored energy). At 7000 miles equatorial, for example, minimum Es for $10^{11}$ J and $10^{12}$ J storage are 75 and 160 MeV respectively.

[redacted] Table 1 enumerates very rough weight estimates for space power systems for the above single ring examples. Projected performance at geosynchronous altitude is also given, although operation at this altitude is dubious.

[redacted] There have been $10^{13}$ J cases noted here. However, not only are the system weights very large but the magnet lengths would be difficult to accommodate. An alternative for the 7000 mi case might be to achieve $10^{13}$ J by projecting 10 rings from five vehicles for a weight of 250,000 lb, which is 16 percent larger than the $10^{13}$ J single ring case but requires correction magnets 150 ft in length rather than the 1000 for the single ring case.

[redacted] Space power system component weight factors were used to obtain a set of weights for each altitude/stored-energy combination considered. As may be seen in Fig. 3, considerable total power increase is to be experienced from losses in retrace correction magnets. The tradeoff of increased retrace magnet weight vs SNAP and loss makeup system weights is reflected in Table 1, where optimum magnet lengths are indicated. In the $10^{13}$ J cases, power system weight variations are shown for different (unoptimized) magnet lengths.

[redacted] DeclASSified



[redacted] Table I

SPACE ELECTRON RING ENERGY STORAGE SINGLE RING PERFORMANCE ESTIMATES (U)

| Energy Stored in one Year (Joules) | Orbit Altitude (s.miles) | Ring Diameter (s.miles) | Electron Energy (MeV) | Power[a] System Weight (lb) | Retrace[b] Magnet Length (ft) | SNAP Unit Power (kw) | SNAP Unit Weight (lb) |
|---|---|---|---|---|---|---|---|
| $10^{11}$ | 3000 | 108 | 130 | 5400 | 10 | 6 | 1190 |
| | 7000 | 311 | 75 | 5000 | 7 | 6 | 1190 |
| | 22,500[c] | 2320 | 28 | 4440 | 3 | 2 | 930 |
| $10^{12}$ | 3000 | 228 | 275 | 30,000 | 225 | 59 | 4560 |
| | 7000 | 670 | 162 | 25,000 | 150 | 53 | 4170 |
| | 22,500 | 4890 | 59 | 18,100 | 80 | 46 | 3760 |
| $10^{13}$ | 7000 | 1450 | 350 | 216,000<br>(199,000 | 1000<br>2000) | 1028 | 66,600 |
| | 7000 | 670 | 162 | 250,000 | 150 | 530 | 35,520 |
| | 22,250 | 10,516 | 127 | 145,000<br>(138,000<br>(165,000 | 1000<br>2000)<br>500) | 564 | 36,900 |

[a] Power system weight includes beam handling devices, electron accelerator, loss makeup coils, retrace-correction magnets, and a SNAP unit for primary power. *Electron converter not included.*

[b] Optimized for minimum power system weight, except for $10^{13}$ J cases.

[c] Geosynchronous orbit altitude.

[d] Two rings from each of five satellites.

[redacted] DeclASSified

[redacted] Declassified



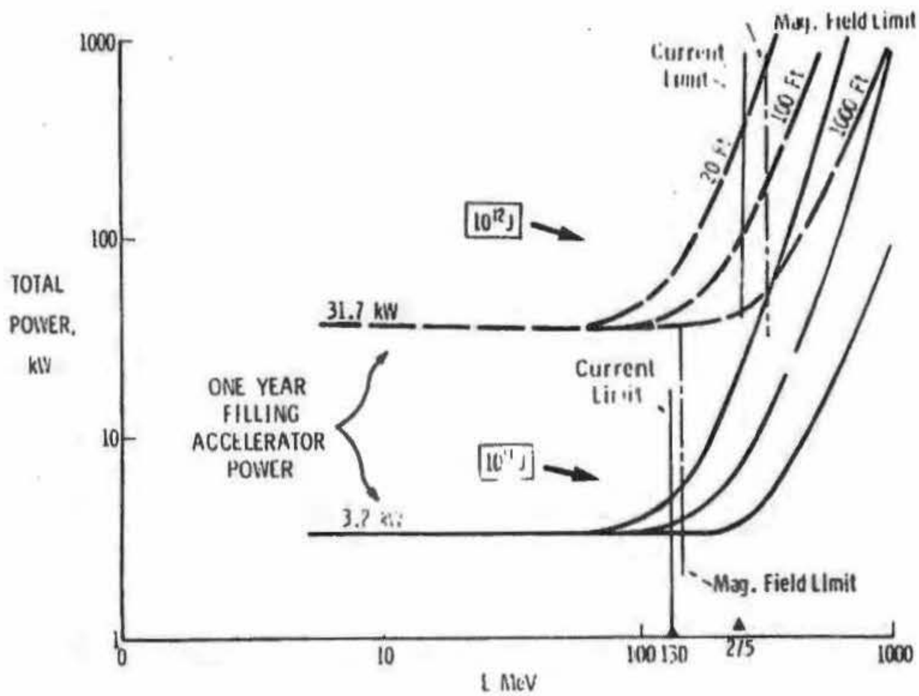


Fig. 3--- Variation of total power needed as a function of electron energy and storage ring total energy and as a function of various retrace correction magnet lengths (U)

[redacted] Declassified

[redacted] Declassified



[redacted] Although higher altitudes permit use of lower electron energies, the weight savings are not significant. Also, satellite payload delivery to 7000 miles is more costly than to 3000 miles. These payload considerations may possibly be ameliorated to some degree by trading time for launch weight. The $10^{12}$ J system, for example, contains a SNAP unit in excess of 50 kw output, which might be coupled to a hydrogen propellant source to produce a low-thrust, high-specific-impulse force for increasing from low (shuttle) altitudes to the 3000 or 7000 mile level.

[redacted] Rough estimates indicate 6000 ft/sec and 10,000 ft/sec as impulse additions to achieve these latter altitudes. Assuming electric arc heating of hydrogen to several thousand degrees Kelvin will yield a specific impulse of ~1000 sec. At this efficiency even the 7000 mi altitude can be attained with 16,000 lb of $H_2$, from an initial (low-orbit equatorial) payload allotment of 60,000 lb. The residual 44,000,lb, of course, does include tankage and r.cket engine weights, but there is still a margin of perhaps 15,000 lb for vehicle structure and weapon system over the 25,000 lb power system weight.

[redacted] On this same basis, a 3000 mile high satellite would require 10,000 lb of $H_2$. Thus an additional 6000 lb of payload would be available (over the 7000 mile high case) but 5000 lb of this would be taken up to additional power system weight.*

(U) Similar comparisons can be made between 7000 mi and geosynchronous altitudes where again improvements in power system weight are approximately offset by additional booster performance requirements.

## SPACE POWER SYSTEM COMPONENTS

[redacted] The general arrangement of the space power system is shown in Fig. 2. Electrical power produced by a nuclear SNAP unit is used to generate electrons by an accelerator, to power makeup coils for electron synchrotron losses, and to operate other elements of the beam handling system. Weight requirements for mechanisms for extracting ring

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*(U) Estimates were made by Atomics International assuming a more optimistic specific impulse of 1500 sec. Their studies showed use of only 5700 lb of $H_2$ in placing a 35,000 lb payload at 5000 miles altitude.

[redacted] Declassified

electrons for weapon or other purposes are included in the beam handling complement, but those of subsequent systems for electron handling and conversion are accounted against the particular user device.

(~~S~~) The space power system involves the production of electrons at power levels in the tens of kilowatts range. Space user systems may have requirements as high as average powers of tens of megawatts. Thus, depending upon user needs and the specific method for electron conversion, the output power conditioning system can range from being very heavy, compared with the space power system, to the converse. Reference (3) treats these various user systems and potential electron conversion schemes. Brief consideration is contained in descriptions of weapon systems selected for discussion purposes.

The SNAP Unit

(U) A nuclear SNAP unit is assumed to be the major source of power. A recent document prepared for ERDA by Atomics International[11] is considered the most up-to-date treatise on this subject. Zirconium hydride (ZrH) space reactor systems of 10 to 75 kWe were considered that used various thermodynamic cycles and conversion systems. Gas-cycle heat engines based upon either the Stirling or Brayton cycles are probably best suited for future space applications. In these systems, heat from the reactor is applied to the hot side of the heat engine by means of pumped NaK liquid metal fluid. Organic coolant is pumped to the engine from the radiator. An alternator is coupled to the engine to produce electrical power. Total SNAP systems weight for the Stirling version varied from 1067 lb at 10 kWe to 4036 lb at 75 kWe; for the Brayton cycle weights were 1389 to 5570 lb. The rubberized weight relation used in these calculations was conservatively based on the Brayton cycle and was $W_{SNAP}$(lb) = 800 + 64 x output power in kW. This weight includes reactor, shield, liquid metal components, power conversion unit (heat engine), heat rejection loop components, radiator structure, and electrical system.

(U) Zirconium hydride reactor space power systems have been under development since 1957. A ZrH SNAP system was placed on orbit in 1965 and amassed over 10,000 hr at full output conditions.

The Ring-Filling Electron Accelerator

[redacted] Electrons of 75 MeV or higher in particle energy are needed for (single earth's field) storage rings. Pulse diode, Van de Graaff, and the Soviet transformer types of accelerators produce electron beams of the order of 10 MeV or less. Superconducting rf linacs can achieve 2 MV/meter so that a pure linac of $\sim$125 ft in length can be considered at this lowest energy level. Probably a better choice is to multiplex the acceleration processes through use of a microtron arrangement. Such a machine could be patterned after the University of Illinois MUSL-2, which uses a 13 MeV superconducting rf linac accelerator segment (supplied by the Stanford HEPL) with 6 to 20 passes through the microtron magnet system to produce resultant particle energies of 70 to 260 MeV.(12)

[redacted] For the cases where $10^{11}$ J are assumed to be stored up over a year's time, a beam output average power of 3.2 kW is needed. This in turn demands beam currents of 20 to 50 μa, the same order of current used in the MUSL-2. (At the $10^{12}$ and $10^{13}$ J levels, accelerators of 32 and 320 kW, respectively, are of course required.)

[redacted] A large part of the energy added to the electron ring store is for loss makeup. The power level for this purpose ranges up to 100 kW or more among the cases explored.

[redacted] The 3.2 kW accelerator for the $10^{11}$ J/3000 mile case is assumed to weigh about one ton. The incremental SNAP weight for powering this accelerator (at high efficiency) is 200 lb. Thus the emphasis should be placed upon weight rather than efficiency, which is why an rf machine is assumed as the microtron driver rather than an induction or transformer type of linac.

Beam Handling System

(U) The various elements for the beam handling system will draw from existing technology of conventional accelerators. In general, deflection magnets will need to use only modest fields (of less than a 1 kG) and will not require high-speed operation. (This assumption is predicated upon a conventional beam format. Some future requirement may demand, say, a chopped beam, where perhaps nanosecond deflection times may be in order. Even here technology would exist for such kicker magnets.(13)

(U) Insertion of the accelerator output beam into the circulating electron stream is not believed to be a problem from phase space limitation (Liouville theorem) aspects because of the relatively slow rate of particle addition and because of electron radiative damping in the ring, particularly enhanced in the retrace correction magnet field. (Methods for dealing with phase-space-limited situations are covered by Peterson.)(10)

[redacted] Servo-control of circulating electrons in the storage ring is also believed to be within the state of the art. Ring circuit times are of the order of $10^{-2} - 10^{-4}$ sec; and the highest frequency disturbances, such as in the earth's magnetic field, have time constants of a second or more. Thus the servo system needed is fairly slow by present-day standards.

(U) Sensing of the returning beam can be performed by a device similar to centering probes such as used on the Bevatron.

(U) Deflection magnets for beam aiming will include very small "shims," which in essence will be sets of small wire coils for vernier control of the beam. The beam extraction mechanism can take the form of a high-speed magnet deflection system when it is desired to extract full-ring-current pulses in serial fashion. Where only a fraction of beam current is desired, then a cyclotron type of "peeler" can be used.

[redacted] The beam handling system will also include a small "ion-oven" device to expel low-speed positive ions into space to keep the satellite surface charge neutral while it is generating and propagating electrons into space (for DE systems but not for a returning beam as in the storage ring).

Makeup Coils

[redacted] In the various cases considered, about half of the energy put into the ring is to overcome synchrotron radiation losses, particularly in the retrace-correction magnet. Thus in the 130 MeV/3000 mi/$10^{11}$ J case, about 3 kW is needed. Although a fairly complex machine is needed to accelerate 3 kW's worth of electrons to 130 million volts, a like amount of power in loss makeup will need only a simple set of induction-accelerator types of coils.* Since the voltage drop per pass for all electrons is miniscule, it is better to apply a stochastic type of acceleration approach and periodically put in the required makeup power, at a fraction of the total circulating electron fluence, and at voltage increments matching conventional electrical systems. In the event a special format is found to be needed in future ring beams, such as ac modulation (as might evolve from a synchronous rf filling accelerator) or a chopped beam, then the loss makeup system can be designed accordingly. It is not expected that this element will require any special development.

Retrace-Correction Magnet

[redacted] The retrace-correction magnet has a very large radius of curvature (a thousand feet or so) and must supply fixed fields of only a few gauss in magnitude to bend the electrons properly. The actual configuration would consist of two parallel strips of air-core coil windings of fine wire. The strips would be a foot or so apart (depending on beam size) and would be nearly straight, since they are segments of only a few degrees. Lengths of the magnet used in reference cases are given in Table 1 and vary from 3 to 2000 ft. The magnet's field must be adjustable over the range of conditions (orbit eccentricity, earth's magnetic field changes, etc.) anticipated. Field current must be minutely controllable to provide necessary beam aiming accuracies.

PARAMETRIC WEIGHT DATA

(U) Table 2 lists pertinent weight relations for various components of the space power system (exclusive of output conversion devices as discussed previously).

[redacted] Accelerator weights reflect a six-fold increase per decade in power. The microtron magnet system is principally the one that varies with increased electron particle energy (i.e., a function of the number

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*(U) The tradeoff of greater Joule losses in field winding conductors (and thus additional SNAP weight) vs increasing conductor size and thus magnet weight indicates a choice of small conductor diameters.

[redacted] DeClassified



[redacted] Table 2

ASSUMED WEIGHT RELATIONS FOR SPACE POWER SYSTEM ELEMENTS (U)
(In pounds)

| | | |
|---|---|---|
| Accelerator | 1500 + 5 x (E, MeV) (3 kWe)<br>10,000 + 30 x (E, MeV) (32 kWe)<br>60,000 + 180 x (E, MeV) (320 kWe) | Accelerator power level, $P_A$ |
| Retrace magnet<br>Weight vs length | 1000 at 20 ft<br>2500 at 100 ft<br>9000 at 1000 ft | |
| Makeup | 16 x ($P_{Losses}$, kWe) | |
| SNAP | 800 + 64 x ($P_{Total}$, kWe) | |
| Beam handling | 1200 | |

of cycles needed to build up to the proper value of E). This value is expected to be much lighter in a space-borne system than in conventional terrestrial counterparts since vacuum enclosures can probably be dispensed with in space. Also, space-charge focusing effects probably can be substituted for conventional magnet focusing systems throughout much of the accelerator system.

(U) The retrace correction magnet will be composed of coils of small wire formed into two long parallel strips. Magnetic fields are expected to be small enough that the principal contribution to weight is just to provide a structure strong enough to withstand beam handling forces in a benign satellite environment. (These are not stressed for vigorously maneuvering vehicles.) The three weights (W) tabulated as a function of magnet length L roughly fit the empirical relationship $W = 186.2\ L^{.563}$ in the units shown.

(U) Makeup coils are estimated at 16 lb per kilowatt of power delivered to make up for synchrotron loss for the circulating electrons. The remaining beam handling components are lumped together in a fixed increment of 1200 lb, reflecting requirements for various control systems whose weight is more or less insensitive to beam power or particle energy.

(U) The SNAP system weight relation was devised to match 10, 25, 50, and 75 kWe cases calculated[11] for the Brayton cycle. At

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extrapolated values beyond 75 kWe, the relation is probably conservative since weights will probably scale at less than a linear rate. Also, the Brayton cycle is not the lightest version studied by AI as previously noted. The Stirling cycle SNAP version weight can be approximated by 600 lb + 46 lb/kWe x $P_T$ (kWe).

## VI. DIRECTED ENERGY SYSTEMS IN SPACE

### GENERAL REMARKS

[redacted]) Directed energy (DE) systems, in general, can be expected to propagate better in space than in the lower atmosphere. This goes without saying for lasers and neutral particle beams. Charged-particle (CP) beams, however, unless at relativistic speeds, will tend to expand rapidly and diverge in space because of like-charge repulsion forces. Existing theoretical analyses[(1)] do not exclude the possibility that relativistic electrons can be propagated with "space-charge" focusing for thousands of miles while maintaining a small, equilibrium beam diameter due to partial neutralization of the beam by ambient ions. Relativistic protons are calculated to have initially somewhat larger beams than electrons and are estimated to become more neutralized at large distances through beam trapping of ambient electrons. In this latter condition a proton beam may begin to approximate the characteristics of a beam of singly ionized heavier positive ions. Such heavier charged particles have also been considered for DE applications. These ions would be less deflected than protons by the earth's magnetic field (for the same total particle energy) but also would be less amenable to space-charge focusing. Cesium ions have enhanced application to collective acceleration methods because of cesium's low work function.

[redacted]) For CP beams to propagate in the lower atmosphere they must create their own conductin, channel through atmospheric "hole-boring." For this phenomenon to occur these beams must have high instantaneous power ($10^{13}$ W as per the Nordsieck condition[(2)]). Also tens of megajoules must be expended by a single "bolt" just in heating the air to form the channel.

[redacted]) This requirement does not apply to propagation confined to space.* Instead of instantaneous beam currents of kiloamperes as needed

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*[redacted]) Ground/air to space propagation, or the reverse, must of course have beam parameters that conform to the lower atmospheric hole-boring requirements. The prospects for a space-to-ground anti-silo weapon are discussed in Ref. (3).

in the lower atmosphere, CPB weapons in space can use currents in the milliampere range. Further, pulses of low total energy and having beam currents of microamperes can be propagated as desired for sensing or communication purposes.

([redacted]) Very long range target kill with an electron CPB makes desirable the use of 7 GeV particle energy. Because of the earth's magnetic field effects, 7 GeV electrons fired along field lines from, say, 3000 miles altitude in the equatorial plane can be directed to a spot (at low altitudes and middle latitudes) roughly 1200 miles in diameter (see Fig. 1). This permitted firing envelope would shrink to 170 miles in diameter if beam energy were reduced to 1 GeV. The area covered would thus reduce to 2 percent of the 7 GeV case, which in turn could have significant effects on numbers of weapon platforms needed to provide certain coverage in defense missions. However, electrons cannot be produced at higher particle energies with cyclic types of accelerators, and that type is the only practical electron machine for space foreseen at this time.

([redacted]) Protons at 7 GeV would have a firing envelope similar to that for electrons. However, because of their greater rest mass, low energy protons would be much less deflected than electrons by magnetic fields. Unfortunately, this advantage probably cannot be exploited, since at less than the few GeV level protons are not very relativistic and would suffer from lack of proper space-charge focusing. Protons at greater than 7 GeV levels can be considered (since they are not limited by synchrotron loss problems as are electrons). If collective accelerators become available for space, permitting protons in the tens of GeV regime, such particles may be highly effective for certain specialized missions.

([redacted]) Another factor relates to effectiveness of CP beams in target destruction. At GeV levels even the hardest of RVs is highly transparent to charged particles. Radiation lengths for GeV level CP beams roughly increase linearly with particle energy. An electron at 7 GeV will deposit only about one-seventh as much of its energy in an RV as a 1 GeV electron; however, it carries seven times as much energy so that the net energy deposited is about the same in both cases. This means

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that the effectiveness of high energy CP beams against targets is roughly independent of particle energy. Of course, proportionately greater energy is needed per electron to generate the higher particle energy beams. Thus there is a tradeoff between coverage pattern and beam energy use, and 7 GeV represents a reasonable compromise in the SPEAR approach. If higher particle energy than 7 GeV could be generated, the greater coverage would reduce the number of satellites needed; but since greater energy would be needed per shot, the reduction in vehicle numbers may well be offset by increased payload needs. However, reducing beam energy while improving the per shot efficiency would require a larger number of satellites, each having less energy storage than the 7 GeV case. Total system costs would probably be greater for that case.

([redacted]) Without rigorous analysis of future space warfare incorporating appropriate scenarios, only general observations can be made regarding effectiveness of DE systems in space. Counterpart (to the SPEAR) studies of use of high energy lasers against RVs (in space)[6] indicate the need for a large number of weapon satellites (e.g., of the order of a thousand in contrast with 4 to 8 assumed for SPEAR). Similar platform number requirements were found in Rand laser weapon boost phase intercept (BPI) studies of ballistic missile defense[4] and more recently by Lockheed in BPI investigations[5] using both lasers and neutral beams.* This comes about because of the divergence of such beams. For a high-power, high-energy laser beam, about a microradian divergence is about the best that can be expected based on present technology. (This also obtains for neutral particle beams.) At this level of collimation, a laser beam will spread out to a 5 ft diameter spot at 1000 miles.

(U) There will be, of course, other space applications where the laser or neutral beam will be as or more effective than CPBs. Against soft targets, for example, the laser may do as well, while not having

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*([redacted]) A group at Rand has studied defense against strategic bombers by laser DE weapon or designator beams from space. Here more reasonable numbers of satellites are found only because of the relatively long transit time of aircraft.

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the firing cone limitations of the CPB. Blinding of surveillance detectors is a possible example of a soft target action.

(U) Another example would be use of a neutral beam against solar arrays.*

(U) In long-range energy transfer by laser (as studied by NASA),(7) lasers again would have an advantage over CPB in flexibility in direction of transmission, although in cases where a CPB can be used, its greater generation efficiency would weigh in its favor.

([redacted]) Figures 4 to 7 schematically illustrate possible arrangements for powering DE beams with a space electron ring energy source. Many of the cases take advantage of the ring electrons' particle energy level. To produce conventional forms of electrical output from highly relativistic electrons can be a difficult problem for some types of conversion processes. Converters of the sort developed by LLL for fusion reactors to regain power from un-neutralized beam particles and from leaking plasma can also be considered for this application. One method less sensitive to electron energy level might be a closed-cycle MHD converter operating at very high temperatures and thus high cycle efficiency. In this case electron energy would simply be thermalized in an engine heat source approximating a Faraday ion cup. Electron-electricity converters are indicated in Figs. 4 and 6.

(U) Component arrangements for the various configurations of Figs. 4 to 7 are reasonably self-explanatory. Further reference will be given in the discussion of specific DE systems below.

THE SPEAR ELECTRON CPB WEAPON

([redacted]) The mission outlined here is one of many possible applications of space-to-space electron beams but was selected for discussion because

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*([redacted]) The $H^{\circ}$ neutral beam concept by Knapp of LASL assumes that a 250 MeV segment of the LAMPF 800 MeV proton accelerator would be placed in orbit. Laser-stripping of the $H^{-}$ ion (after beam aiming) is needed to achieve 1 μrad divergence; gas-stripping will cause several times higher values of divergence. Both particle energy and beam current of this machine are limited to levels unsuitable for weapon kill of hard targets. Soft targets similar to those considered for weapon lasers can be considered as well as the solar array damage mentioned above.

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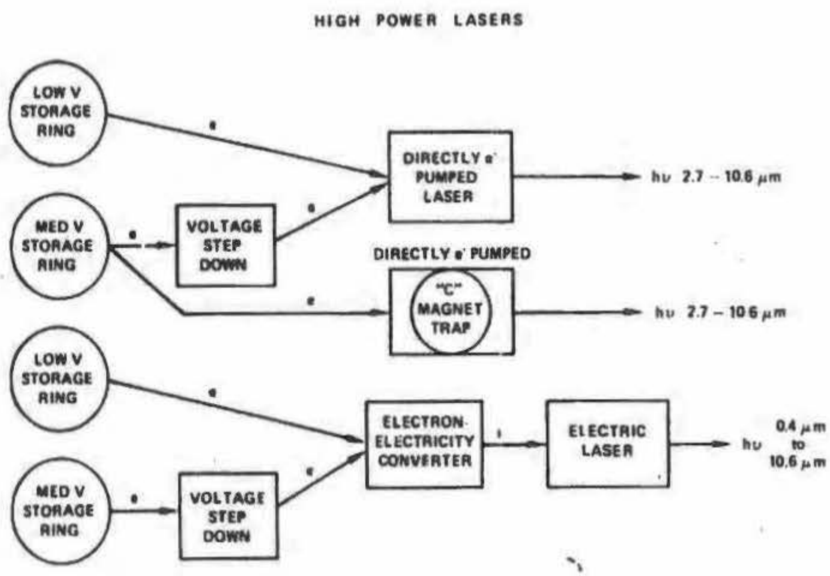


[redacted] Fig. 4 — Candidate radiation weapon systems [redacted]

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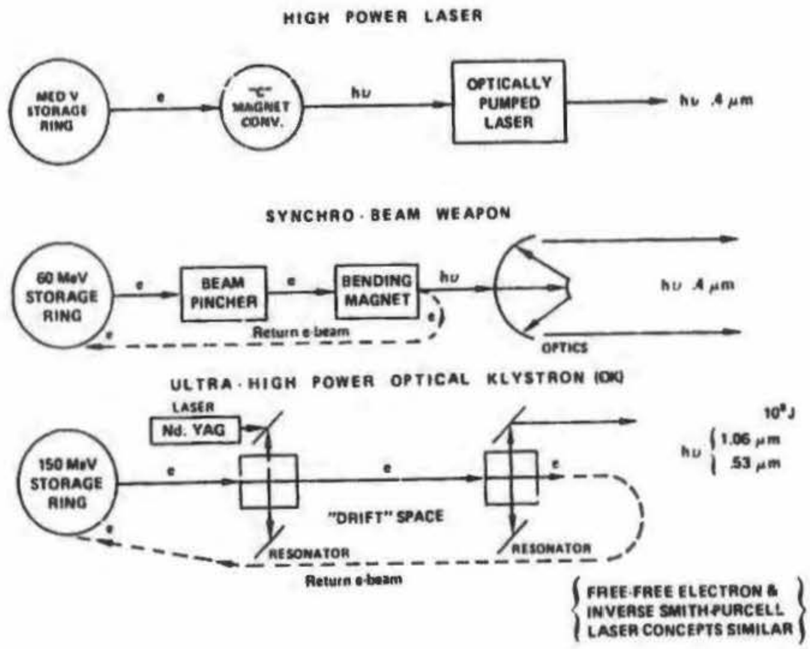


[redacted] Fig. 5 — Candidate radiation weapon systems ([redacted])

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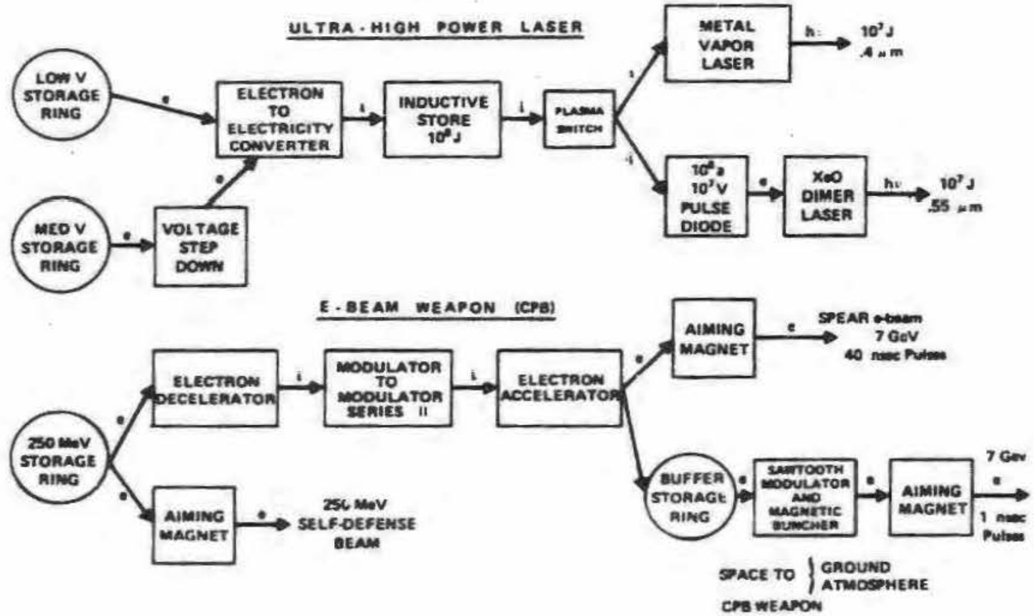


[redacted]) Fig. 6 — Candidate radiation weapon systems ([redacted]



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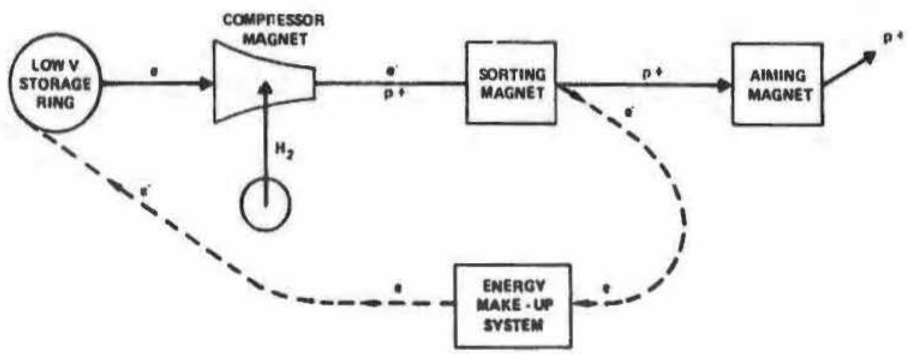
PROTON BEAM WEAPON

COLLECTIVE ACCELERATUR




(U) Fig. 7 — Candidate space radiation weapon system (U)

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of typical requirements for system components and functions, and because of its potential importance.

([redacted]) A four-satellite array is assumed with the vehicles equally spaced in circular, retrograde equatorial orbits at 3000 statute miles. The principal targets are submarine-launched strategic missile warheads (RVs) arriving in the ZI from the Pacific (see Fig. 1). For such targets the array provides continuous coverage assuming due south-to-north firings of the beam. Other RVs, either land-launched or sub-launched, and arriving over the ZI, potentially also can be handled. These latter will not always be in an optimum due-north firing position from one of the four satellites.

([redacted]) The array can attack other exoatmospheric missile targets in the 27° to 48° latitude zones of both Northern and Southern Hemispheres. It can also perform communication and anti-space-vehicle functions. (A second four-satellite array at 7000 miles can be added if desired to attack RVs in the 48° to 64° latitude bands.)

([redacted]) The system is designed to fire along field lines in approximately the L = 1.75 shells (of a dipole field representation of the earth's magnetic field). An electron particle energy of 7 GeV is assumed. This energy level is a compromise between one that is high enough to be useful with respect to bending effects of the earth's magnetic field but not so high that it is difficult to generate the electrons or that the RV becomes too transparent to them.

([redacted]) Firing ranges are of the order of 5000 statute miles. Because of the magnetic field perturbation, a particle beam fired at an angle to a field line will tend to spiral around this line. The 7 GeV beam will rotate about one-half turn in traversing its path to the target.

([redacted]) The satellite can determine only where the end of the electron beam is when the beam strikes the RV. Knowledge of the instantaneous values of the earth's field (both from sensing and stored statistical data) and extensive in-space pre-calibration of beam projection will probably permit computation sufficient to project the beam in the near vicinity of the RV (1 km CEP assumed). Accuracy of $1:10^4$ is required. The accelerator assumed for this mission puts out 12 million 40-nanosecond pulses per second. These are laid down in a pattern whose mesh

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is small enough to include at least one shot on the vehicle.* Impingement of this precursor beam on the RV will give out characteristic signals (rf, neutrons, $\gamma$-rays, light, etc.), some of which may be picked up by the attacking satellite. Detection may be augmented by swarms of orbiting detector packages that relay time of detection of a precursor hit. Sensitive telescopes exist for the various types of emanation. For optical detection, about 1 kW/steradian is radiated in all bands and is detectable by sensors peaked for characteristic frequencies and location. The plasma spewing out from the target (backscattered from the impinging beam) will act as a stub dipole antenna in giving off rf radiation. Because of the shortness of each precursor pulse (40 nsec), the rf signal generated will exhibit a characteristic signature, providing another possibility for hit detection.

[redacted] It is estimated that the original uncertainty in beam coordinates will be of the order of a kilometer so that the RV will first be detected in a fraction of a second by the precursor beam in a search mode. If the destruction pulse is then generated in a short period, the total engagement time should take about a second. Upping the beam current from the 100 microampere precursor level to the 10 milliampere level will permit killing the RV in about 1/7 of a second or so. Average power to the accelerator at the latter levels will be 75 megawatts.

[redacted] The accelerator assumed for SPEAR is a version of the Rand-conceived Cylac[14,15] machine. More details of the SPEAR accelerator may be found in Ref. (3). This type of accelerator is midway between the electron synchrotron and the induction linear accelerator (linac) in characteristics. Electrons in a Cylac are given large increments of acceleration compared with the synchrotron, which greatly reduces the number of circuits around the machine. Thus, resonance instabilities typical of the synchrotron are overcome. In the Cylac machine concept, induction accelerating elements operate many times on each electron instead of just once as in the case of a (one-pass) linac.

(U) An innovative feature of the Cylac arises because relativistic electrons are all at very nearly the same velocity (acceleration

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*[redacted] Lyons and Bussard[6] use a precursor barrage scheme similar to this in their investigation of space-borne anti-RV laser weapons.



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makes them more massive rather than go much faster), and accelerating modules can be used for a variety of electron energies. Further, electrons can be passed in either direction through a core. This latter feature eliminates the need for core reset pulses (thereby effectively cutting hysteresis losses in half and permitting much higher modulation frequencies).

[redacted] The accelerator assumed for SPEAR takes advantage of these concepts and improves on them with variations permitted in space-borne machines.

[redacted] Two sets of 40-nanosecond-long electron bunches are assumed to circulate at all times in the accelerator. These two sets are going in opposite directions so that each electron passes by $7 \times 10^{15}$ electrons going the other way during its acceleration period. However, the prospect for collision is negligibly small (and can be made even smaller by magnet schemes as used in two-way FFAG accelerators).[16] Electron bunches are phased so that induction accelerator cores can alternately accelerate in opposite directions. In fact, such a scheme permits use of sine-wave modulation just as in conventional alternating current systems.

[redacted] The specific geometry chosen as a possible SPEAR machine is shown in Fig. 8. The accelerator is composed of four sets of 10 MeV induction linac segments arranged in a square ring. The total circuit time for one turn is 640 nsec or 160 nsec per side. Thus a core accelerates one way for 40 nsec, reverses polarity for 40 nsec, accelerates the other way for 40 nsec, and again reverses for 40 nsec. Modulators work at a 6 MHz frequency.

[redacted] Each of these four linac segments is made up of ten 1 MeV double ferrite core induction modules similar to the Omnitron developed a decade ago by LBL.[17] The ring electron path is 640 ft in circumference; each side is 160 ft long. Particles of each of 190 energy levels (between 5 MeV and 7 GeV) are contained in every 40 nanosecond pulse circulating in the ring. Only 175 levels would nominally be needed to produce an output pulse of 7 GeV, but 190 are actually required because of synchrotron losses at the higher energy levels. Corner magnets will be air-core electromagnets of constant 15 kG fields.

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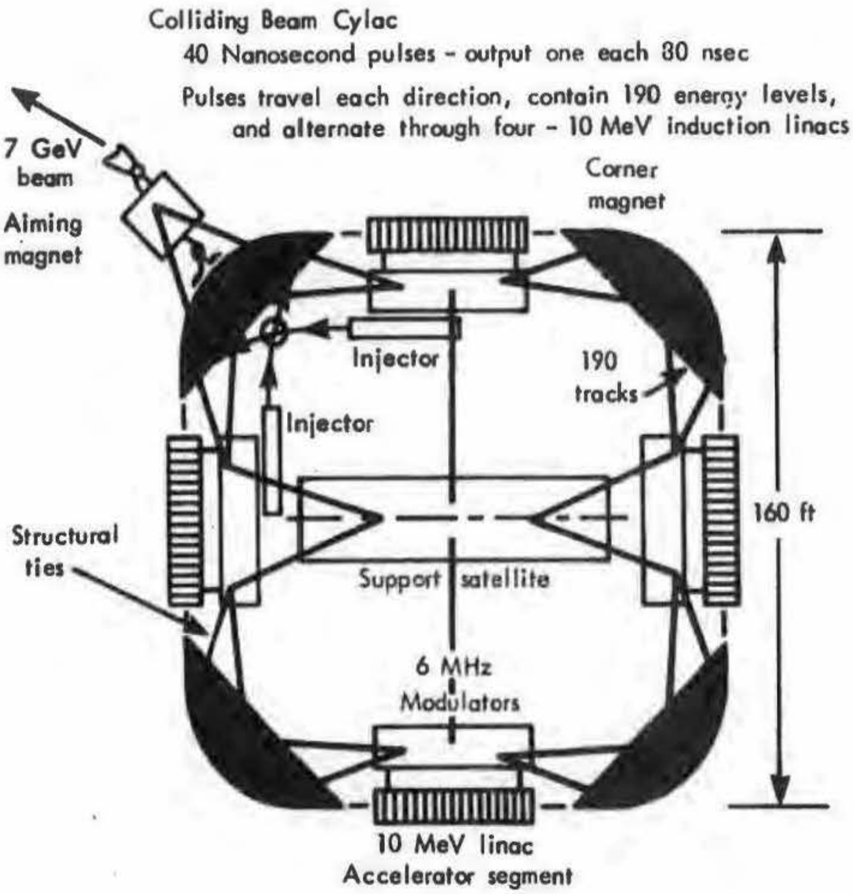


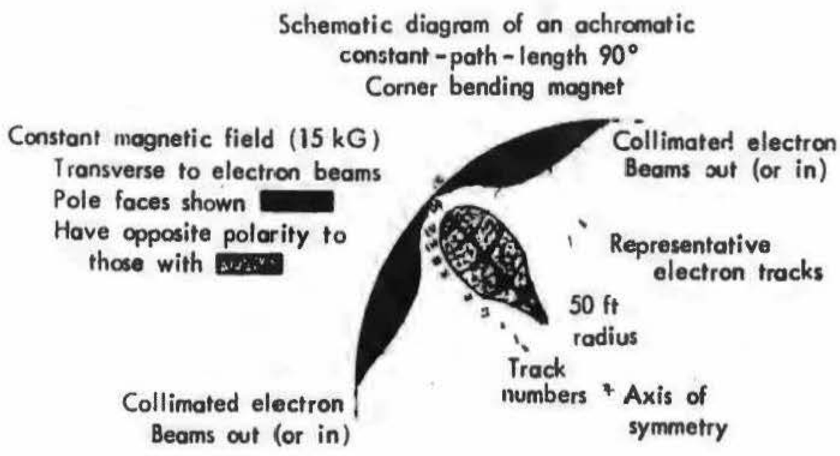


Fig. 8 — Space accelerator for SPEAR ( )

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A pair of sector magnets is arranged so that electrons of different energies are coaxial both entering and exiting. Another sector magnet of opposite polarity is inserted between the first two magnets, and pole face edges of all three are so arrayed that electrons of all different energies have the same path length.

[redacted] Electrical energy to induction linac modules is supplied from an electron power storage ring as illustrated in Fig. 6. Among the various electron energy conversion options the following transformer-like scheme is favored. Here ring electron particle energy is stepped down by an electron beam decelerator having an arrangement analogous to that of the SPEAR accelerator. By a proper series/parallel circuit arrangement, electrical energy from the storage ring beam decelerator modulators can directly energize a corresponding set of SPEAR accelerator modulators.

(U) The entire SPEAR accelerator structure will be held together by lightweight connectors and assembled in space. The size of units involved is believed to be compatible with present Skylab and future shuttle vehicles.

[redacted] Various methods for optical location of target RVs can be considered and probably a combination of these would ultimately be used. DSP and other surveillance systems can provide initial boost detection and some indication of the midcourse trajectory. Passive detection for midcourse tracking has been researched, including preliminary development of critical sensor elements. Such devices could be placed on the SPEAR vehicles (since most RVs will appear above SPEAR's horizon, it generally will be viewing these targets against an outer-space background) as well as on other satellite systems as may be available. SPEAR might also perform active or semi-active radar tracking. With the distances involved, a laser tracker is probably the best choice (from a space vehicle). In the semi-active mode, return signal pickup could be performed by the same set of transponder vehicles considered for detection of precursor beam target impingement. The laser radar system has considerable similarity to a laser DE weapon and may in some cases use common elements. Further description is included below.

LASER DE SYSTEMS

[redacted] Currently conceived high-power, high-energy laser systems foresee optical system divergences as low as a microradian. Laser radar systems forecast accuracies a decade better. These estimates must include vehicle attitude control accuracy, problems of structural settling after mirror slewing, effects of transient heating, etc. It is assumed that some sort of computer-directed adaptive focusing and boresighting techniques will be an integral part of such systems in the future.

[redacted] Estimates based upon Rand weapon laser studies are that perhaps future weapon beams of 1/3 $\mu$rad divergence could be projected from 3000 or 7000 mile vehicles; because of greater quiescence and special orientation features at geosynchronous altitudes, 0.1 $\mu$rad is forecast for this altitude.

[redacted] A laser sensing beam at SPEAR ranges of 5000 miles might also represent a weapon beam at shorter ranges against soft targets. Assuming 1/3 $\mu$rad divergence, a laser beam projected 5000 miles from a SPEAR vehicle will have a 2.7 m (8.8 ft) diameter spot. A 50 MJ laser pulse would place approximately $10^3$ J/cm$^2$ on a target at that distance, which is in the general range of energy densities needed to disable, say, a ballistic missile booster in a boost phase intercept (BPI) function. A $10^{12}$ J energy store could supply $10^3$ to $10^4$ of these pulses at laser efficiencies of 5 to 50 percent. Lower energy per pulse or higher energy density on target could possibly be attained by a second set of mirror-bearing satellites near the target area that receive and retransmit the laser beam, refocusing it on the target. Such a relay vehicle, 500 miles from the target and having 1/3 $\mu$rad optics, could theoretically increase energy density on target or numbers of pulses by a factor of 100. The geometry of the relay approach poses difficulties; also, a substantial number of relay satellites would be needed to provide useful coverage. Such numbers of vehicles can perhaps be tolerated if these are small detector/transponder packages, as in the case of the SPEAR hit-detection system. However, the mirror-bearing relay vehicles need to carry mirrors of over 10 ft in diameter along with tracking and focusing systems and are fairly sophisticated vehicles.

([redacted]) Another choice is to send a SPEAR e-beam to power a relay satellite weapon laser. However, that would be trading an optical relay problem for an e-beam reception problem.

([redacted]) A logical compromise would be to incorporate a high-power laser in the SPEAR vehicle that can perform direct BPI on targets of opportunity under appropriate conditions of range and satellite position. The same laser system would also be available for ASAT functions having various kill, disablement, blinding, etc. probabilities as a function of range; and at reduced power levels the laser system could also be used for SPEAR target-tracking.

([redacted]) It is assumed that a laser in the visible spectral region (0.4 μ or 400 nm) is a reasonable choice for future DE systems. The wavelengths involved represent a decade improvement in linear dimensions over currently considered IR lasers, which in turn may translate into a 100-fold to 1000-fold improvement in optical system volume and weight. Proceeding to shorter wavelengths in the uv region while offering further reduction in system size begins to invite problems in energy throughput because of these reduced sizes. Besides, uv lasers are still in a basically unknown status;[18] also good optical reflector materials at wavelengths below 0.1μ have not been achieved.

([redacted]) Something like a 4 m (13 ft) diameter mirror is in order (diffraction limit at .4μ is $10^{-7}$ rad). Much of the laser system weight would be tied up in the secondary optical system of which the mirror is a major element. The difference in size and weight between a BPI weapon laser of the type described above and a laser radar for SPEAR at perhaps two decades less energy is probably not significant. The weapon laser package (not including power supply, which is already included in SPEAR) is estimated at 25,000 lb.

([redacted]) Various types of potential lasers in the visible spectrum are included in the block diagrams of Figs. 4 to 7. Metal vapor lasers such as the copper-halide type are expected ultimately to produce 10 percent efficiency.[7] From storage ring e-beam energy to DE output, the efficiency might be more like 5 percent. The same applies to the XeO laser as a representative of a number of new noble gas dimer lasers being researched by SRI[19] and LLL.[20] Here in addition to converting electrons to electricity to perform weapon pulse storage, a pulse diode must be used to produce 10 MeV electrons needed to pump the laser. Again about 5 percent is about the best we can hope for.

([redacted]) Use of a doubled Nd:YAG laser beam (at 0.53μ) in an optical klystron (OK) is depicted in Fig. 6.[7] Since one uses electrons directly from the storage ring and these are repetitive, this laser beam amplification process can be highly efficient—perhaps 50 percent.

([redacted]) Lasing in the infrared has been studied in the free-electron laser experiments at Stanford.[21] Both spontaneous emission and amplification of laser beams have been demonstrated. There is expectation that visible spectrum versions of this laser can be achieved. Use of 120 MeV in the same standard device, for example, should produce .43 μm radiation. Efficiency per electron pass is low, but direct use of storage ring electrons could (as in the OK approach) greatly improve this condition.

([redacted]) Yet another variation similar to the above system is that of direct use of synchrotron light from deflections of the storage ring electrons. By pinching the e-beam[22] and simultaneously putting it through small deflections in a high intensity solenoidal supermagnet field, a very small diameter extended light source is produced. Long-focal-length optics with anamorphic correction elements for the extended source theoretically permit optical beams of a few μrad divergence. Optical power produced is calculated in the $10^7$ to $10^9$ watt region.* Light from about .1 to .5 μm is produced in a roughly Maxwellian distribution.

([redacted]) This optical system, labeled a "synchro-beam" device, requires only a small-sized attachment to the electron-beam storage ring to produce the source emanation. The remaining optics are comparable to secondary optics for a weapon laser. Thus there would be hardware reduction plus the benefit that the efficiency of this generator system

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*([redacted]) The free-electron laser uses a spiraling, transverse magnetic field to interact with and selectively produce spontaneous, coherent optical radiation. In contrast, in the synchro-beam device, the *electrons* spiral in a uniform field. Expected luminance of the synchro-beam device is much higher; even at 120 MeV a 5-meter-long free-electron device coupled to an Electro-ring could produce only a few kilowatts of laser beam power.

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is theoretically over 90 percent. In the case of the high-power weapon laser, the only use made of the laser's inherent coherent and monoenergetic properties is to produce a small divergence beam. Thus, if there were a synchro-beam with several times the divergence but ten times the generation efficiency, equal energy density can be placed on targets with the synchro-beam but with a larger spot than a laser. These same considerations also apply to laser energy-transfer schemes. Review of the NASA work showed that only one of many of its conversion schemes required coherent beam properties.[7]

OTHER DE APPLICATIONS

(U) The preceding material covered CPB and laser DE weapons. Many analogies for other space applications are immediately apparent. Discussion has been made of the commonality of the laser weapon and laser radar systems. Also mention has been made of space-to-space CPB and laser power transfer and the prospects that laser power might also be transmitted to and from terrestrial locations. More detailed treatment of this subject will be found in Ref. (3).

(U) These previously described CPB and laser systems can be considered as an aid to hardening of space communication links. Laser communication systems are under development in many arenas, including ground-space links for the Air Force. The SPEAR beam itself might be used as a data link by treating the 40 nsec pulses as bits yielding a 12 MHz digital rate capability. Alternatively, the precursor pulses might be given digital or analog coding to create an even greater signal bandwidth. Use of electrons at lower energy levels (such as storage ring electrons) will result in reduced direct point-to-point ranges. However, with low energy ($E < 1$ MeV) electrons, use of electron drift because of the earth's magnetic field gradient would permit trapped e-beams to spiral back and forth along field lines while "drifting" circumferentially around the world. Communication in this mode might take advantage of the recent ARPANET packet communication techniques. The effect of mirroring of the electrons along field lines on beam-encoded messages is an unknown.

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([redacted]) In the more conventional manner, the ultra-high power available from the storage ring can be used (along with appropriate rf generators such as the auto-accelerator)[23] to produce very-high-power rf links for protection against jamming. This same rf generator can be used for jamming or for microwave radar purposes. It may be desirable, for instance, in times of hostilities to operate a high-power radar for several days at power levels several hundred times greater than available from SNAP systems. Such radar can be considered to provide a master beam in a broad, semi-active function, or be a tracking system, or provide designation for long-distance homing systems.

([redacted]) Creation of auroral effects by electrons is another application, and here again storage ring electrons might be used directly.

(U) Particle beam imaging, material excitation, and satellite "x-raying" are possible uses in an inspector role.

[redacted] Declassified

## VII. DEVELOPMENT PLANNING

([redacted]) Discussion of a logical program for development of electron DE and storage ring concepts is presented in Ref. (3). A brief summary of such a program is given below.

([redacted]) In the near term, further theoretical investigation is needed of physical, engineering, and economic aspects of electron systems in space, particularly detailed analysis of space storage ring propagation, including examination of potential dynamical instability modes. In addition to the major topic areas, peripheral studies of potential safety hazards, environmental effects, and political implications should be performed.

(U) A second near-term program is that of mission application analysis. Here typical system performance ranges should be assumed and used in weapon system studies to determine the potential value of weapon (or other) beams and storage rings as a function of expected performance and against selected future space warfare scenarios.

(U) Based upon the system formulation output of the above two task areas, development planning should be performed taking into account proper time-phasing of R&D segments and appropriate milestones to be achieved as a precursor to further development.

([redacted]) The first logical step in such a development program is an in-space experiment to demonstrate the principle of space-charge focusing of an electron beam propagating in space and receiving partial beam charge neutralization from the presence of ambient ions. Initial phases of such an experiment can be quite simple since (in distinction to beams propagated in the lower atmosphere) there are no minimum restrictions as to beam current. Thus a fairly small* (and perhaps readily convertible from existing terrestrial technology) electron source can be considered for this purpose. Modes for launching this experiment include

*(U) Although verification of space-focused propagation of a low-current e-beam is an essential precursor to further concept R&D, there are possibly nonlinear high-current effects that must be explored in follow-on in-space experiments of the Electro-ring.

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piggyback on special purpose satellites, sharing a Standard Satellite payload, or perhaps forming a secondary objective of early experimental shuttle flights. No beam handling functions are perceived except for a programmed set of beam projection angles. A set of detectors would be emplaced to pick up any returned electrons. This proof-of-principle demonstration should also provide crude indications of beam quality degradation in the returned beam.

[redacted] Concurrent with this early experiment should be the initiation of bread-board R&D of long-lead-time critical system elements. These include lightweight, high-modulation-rate accelerators; beam handling devices and control systems; and ring-electron energy conversion systems.

[redacted] The next major program step is to place payloads in space to perform experimental development of space-borne beam generating and beam handling equipment. This is a key to feasibility of the space electron application concepts. The storage ring beam handling equipment, for example, will need to be properly designed to inhibit buildup of potential ring instability modes; if improperly designed, it actually can be a principal source of such instabilities.

(U) Iteration between results of space-borne experimentation and system component development is perceived. Such a process will be enhanced in the shuttle era by the reduction in the necessity for a high degree of space hardware qualification as in the past.

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