RF LINACS FOR ESOTERIC APPLICATIONS*

R. A. JAMESON, AT-DO, MS H8II
Los Alamos National Laboratory, Los Alamos, NM 87545

Summary

Particle accelerators of various types have been considered for many years in terms of their application to national defense. Recently, the Strategic Defense Initiative has focused and emphasized such applications. After appropriate and extensive development, accelerators could fulfill important roles in a defensive-system architecture and could compete effectively with other technologies. A great deal of the required development is engineering. Aspects of the R&D program on rf-linac-based applications are discussed, and potential long-term influences on accelerator technology are outlined.

Introduction

Particle accelerators, in their most prosaic form as viewed by the aficionado, seem to the hoi polloi most mysterious and strange—esoteric. The initiate is excited by the striking, unusual, or imaginative new proposal or the challenge of actually making the idea work. In our world, accelerators are exotic. They become perhaps more so, the more one works and learns; dedication and creativity of high order are apparent in any gathering of enthusiasts. Consider the audacity of confining lightning in a room and using it to perform precise manipulations on invisible particles—as accomplished by Cockcroft and Walton; the extrapolation of a room-size electron linac to a linac two miles long at SLAC; a leap of four orders of magnitude in the intensity of operational proton beams at LAMPF. We are considering the Superconducting Super Collider (SSC), a circular machine 60 miles in circumference, and it was imaginatively postulated that such a machine might be floated on the world's oceans, using the beam to map the earth's core.[1] We seriously discuss colliding two beams of enormous power at a focus of micron or even angstrom dimensions in our efforts to understand the most basic constituents and properties of matter. High-brightness heavy-ion beams may be the most viable possibility for inertial confinement fusion, and high-intensity light-ion beams are the central ingredient of other fusion schemes or materials test facilities.

Likewise, since accelerators were invented, their possibilities as directed-energy systems have been realized and have stimulated research. Because of the enormous power requirements and other technical difficulties, such possibilities have always been elusive and still are. However, in the more recent past, the continuing threat of nuclear-offensive weapons, the rush of progress in science and technology on all frontiers, and (in particular) the remarkable achievements at the frontiers of space came together in President Reagan's 1983 directive to focus more of this research under what is now known as the Strategic Defense Initiative (SDI).

A visit to the space exhibits at the Smithsonian Institute convinces one that accelerators could be made to operate in space. Whether it is reasonable to believe that they could be scaled to serve as defensive weapons devices in any given amount of time, or at a bearable cost, is another question entirely, as is the question of whether an extremely complex network of such systems is manageable, even under ideal conditions. Given the status of small, but powerful, nuclear weapons that can be deployed by cruise missile or suitcase, it is clear that an ICBM defense only is not sufficient. Whether such a system could help prevent humanity from perpetrating another Dark Age (or worse) while it tries to learn how to use similar systems to reach the stars is perhaps the hardest question to answer about SDI. It is part of our responsibility as accelerator scientists to help chart a responsible R&D course and to participate in the national debate on the issues.

President Reagan's challenge was to investigate, through a research program over the next few decades, a defense against nuclear weapons. It was not long before large and costly integrated experiments in the near term were proposed. The relative merits of many ideas have been hotly debated, particularly in terms of scalability and long-term utility. The importance of particle beams, and the relatively advanced state of the technology for producing them, came to be widely recognized—so much so that particle-beam technology is the core of two out of the three Integrated System Experiments (ISE) now planned for directed-energy defensive-weapons research. These three ISEs will test the space-based neutral-particle beam (NPB), provided by an rf linac; the free-electron-laser (FEL), driven by an induction linac (IL) in a ground-based version, complemented by an rf-linac-driven FEL, as a backup space or ground-based approach; and a tracking and pointing system.

The initial ISEs do not presume to arrive at full-scale systems capable of defense against ICBMs. Such a system, if ever feasible, is surely a long-term proposition. The SDI will attempt to prove key concepts through sequenced ISEs and the associated R&D and technology-base development that supports each ISE in turn. Within a given program, the ISE and the long-term developments to support the ISEs following in the sequence are carefully scheduled; thus, in any year, activities are spread between near and far term.

A look through the literature and at the agenda for this conference clearly shows that high-brightness accelerators have become the topic of the day in many, or most, areas of accelerator application. Below, we frame some of the central issues and programs relevant to the high-brightness rf-driven linear accelerators needed in the SDI research program.

Brightness and Tradeoffs

Extrapolations in both the physics and engineering of rf linacs, as commonly interpreted in the accelerator community, are needed for today's advanced applications for physics research, defense, heavy-ion fusion, or materials-testing. A common figure of merit is the beam brightness expressed generically, and variously, as the power (sometimes only the current) per unit of phase-space area or volume, depending on the application. (Phase space describes the physical size and the angular divergence properties of a beam; the unit area is called emittance.) Hitting a spot requires the beam power to be confined to a particular transverse area; if there are energy or time-dependent effects that are important to the application, then the longitudinal phase space must also be controlled. It is usually the average power that is of interest, whether to achieve an adequate data rate in a high-energy physics machine or to achieve the purposes of a defensive system. High average current requires large amounts of supply power and, because of waste heat, demands sophisticated engineering techniques.

Both high current and high quality require a detailed understanding of the physical limitations of accelerating and transport channels. Seminal progress has

*Work performed under the auspices of the U.S. Dept. of Energy and sponsored by the Strategic Defense Initiative Organization through the U.S. Air Force and U.S. Army Strategic Defense Command.

been made in this area in the past decade, requiring the extension of the classical accelerator physics to include plasma and collective nonlinear effects. As the beam becomes more intense, it generates self-fields (space charge) or interactions with its surroundings (beam-breakup effects) that tend to defocus it. These self-fields must be carefully balanced and matched to externally applied fields provided through the accelerator structure; if high quality as well as high intensity (that is, high brightness) is to be preserved, the problem becomes especially challenging.

If more beam power is needed than can be supplied by a single channel, then multiple channels could be provided. However, to maximize efficiency, it is clear that each channel should be operated as close as possible to the space charge or beam-breakup limits. With modern techniques of multiple-drive power sources and automatic control, the beam loading (ratio of the power actually delivered to the beam to the sum of beam power and the power required by the accelerating structure itself to establish the external fields) is high: 50% or more in room-temperature machines and 90% or more in superconducting systems. Therefore, the cost of more beam power achieved by multiple channels is roughly proportional to the number of channels, although some savings can be obtained by engineering common rf field, vacuum, or cooling envelopes.

Similarly, the increase in beam brightness, produced by reducing emittance, is a strong effect, requiring care with each channel as well as consideration of whether and how multiple channels may be recombined. For example, channel constraints are more severe with low-energy ions; therefore, after initial acceleration, channels could be combined for better efficiency. Or, target considerations could affect the way the multiple-channel system is configured.

We thus begin to see that the brightness formula implies a host of system parameters and tradeoffs that affect the current and/or quality achievable and the price (in terms of cost, weight, or other factors) for achieving the desired brightness. Great care must be taken in defining the optimization problem because the imposed constraints can change the approach drastically.

Some considerations impose fairly strict boundaries with techniques or materials now available: for example, the maximum surface rf field achievable without sparking or the maximum magnetic field available from permanent-magnet material. Some parameters produce a monotonic improvement in brightness; for example, a higher frequency produces better brightness in an rf ion linac channel operated near the space-charge limit. However, consideration of the heat-removal problems at large duty factor or continuous operation places limitations on the maximum frequency, with the result that the best frequency choice is within the broad range of 300-500 MHz for very high power, high-brightness ion rf linacs. This example illustrates another important point—that suboptimization for a short-term problem (for example, an objective that could be explored at low duty factor) could produce an unwarranted diversion of effort from the long-term problem (that would require a cw device).

A calibration of the brightness requirements for a few applications of interest is instructive. In high-energy physics (HEP) research using colliding beams, the brightness requirement on the accelerator is combined with probabilities of events occurring in the physics experiment, in an expression called the luminosity. Long-range luminosity goals of $10^{33\text{-}34}$ cm^{-2} s^{-1} at energies in the 3-TeV range are sought for electron colliders, compared to the design goal of 6×10^{30} cm^{-2} s^{-1} at 50-GeV energy for the Stanford Linear Collider now under construction. Heavy-ion fusion (HIF) places severe requirements on a six-dimensional peak brightness, thought to be achiev-able using multiple beams from induction linacs or rf linac plus storage-ring configurations. In FEL lasers, the electron-linac brightness must match the requirements of the laser beam. Radio-frequency linacs with peak brightness of around 10^{11} A/m^2 · rad^2 are contemplated to drive FEL oscillators, with 10^{10} now operational; induction linacs for single-pass FELs need 2×10^9 brightness, with 5×10^7 at present.

Neutral-particle beams penetrate inside materials, depositing their energy at a depth determined by the particle's dE/dx characteristics for the material. This penetration is a notable advantage of particle beams over photons because it is very difficult to harden a gainst. Typical materials melt when exposed to around 1 kJ/g; with a penetration of 10 cm and nominal density of 2 g/cm^3, 20 kJ/cm^2 illumination is required, and for a 1-m^2 target, 2×10^8 J are required from the device. The Fusion Material Irradiation Test (FMIT) 80-MHz linac was designed for 100-mA average current (and achieved 40 mA at 2 MeV before the program was canceled); thus, at the energy required for 10-cm penetration and 100-mA total beam current, with the 40% core of the beam on the target, one could get within a factor of 20 of the goal. However, if the target is far away, the angular divergence contribution to the brightness requirement is crucial. As indicated above, a higher frequency linac would be used, complicating the engineering problems, and emittance would have to be carefully controlled throughout the system. Again, the overall challenge turns out to be around three orders of magnitude in brightness.

So HEP, HIF, FEL, and NPB devices all have similar challenges and similar problems and approaches to solutions—the basic problems of attacking the numerator or the denominator of the brightness equation. The numerator can be raised by brute force, but the large power requirements and engineering problems are formidable, and better system efficiency is very desirable. Power scale-up may tend to spoil the beam quality because of intensity-related phenomena. Emittance preservation in each case also requires that aberration effects in the transport optics be avoided. Thus, a long-term development program in advanced linac-based drivers is required, with a judicious mix of long-range R&D aimed at changing the basic technical or economic constraint set, along with evolving integrated demonstrations to be sure there is a continuing focus on the overall problem.

Neutral-Particle Beams

A neutral beam would not be influenced by the earth's electric or magnetic fields and thus could be accurately propagated over a long distance. However, for the light-ion (principally hydrogen) beams that have practical possibilities, the binding energy of the electron is not high, and the beam can be stripped back to a charged state by collisions in the atmosphere. Therefore, the NPB is only usable in space, down to perhaps 100 km from the surface. A system concept is shown in Fig. 1. The present and speculated future characteristics of the targets (their probable distribution, trajectories, countermeasuring, hardening, and so on) and the corresponding requirements on the NPB platforms that might be part of a multi-layered defensive system are being exhaustively studied and debated. The NPB, because of its penetrating power and interaction characteristics in materials, could serve a variety of functions, including discrimination between warheads and decoys and destruction at various levels from electronic upset to outright demolition.

As outlined above, the NPB research program comprises a series of ISEs, supported by a strong program of continuing research, component and system development, and testing. Focus is provided by actual flight experiments led by the aerospace industry and tied to the continuing development program through an integrated Ground-Test Accelerator (GTA) facility at Los Alamos.

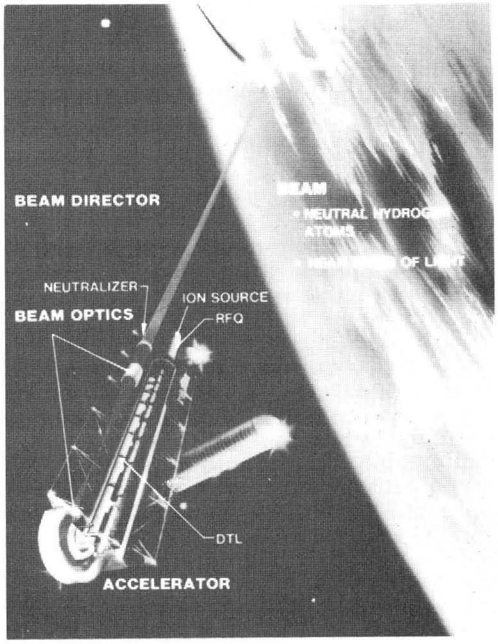

Fig. 1. Neutral particle beam system concept.

With strong industry involvement, a full-scale system will be continuously evolving in the GTA facility, at all stages kept close in concept and components to a flight-qualified system but without requiring it to be fully qualified. New components, experiments, and control ideas would be tested in this system environment. After the information needed for an ISE has been obtained and transferred, the facility will be retrofitted to consolidate the R&D for the next ISE. The actual flight equipment and flight support will be provided by the aerospace industry.

A feasibility study was completed in 1985 by three aerospace contractors and Los Alamos[2] for the U.S. Air Force, developing a shuttle-based recommendation for the first ISE as shown in Table I and Figs. 2 and 3. The primary-mission objectives are to operate an NPB accelerator in space and characterize the output beam, measure the beam at a remote target, and evaluate the discrimination of objects of high and low mass. Secondary objectives include checking the ability of the system to measure other signatures of beam-target interaction and testing advanced detector concepts.

An elliptical orbit might be used to facilitate atmospheric penetration studies. The 50-MeV output energy compromises between energies representative of a target discriminator, the minimum energy needed for useful scientific experiments, and the weight and length constraints of the shuttle. Other features are based on the state of the art, and a low duty factor was chosen to reduce rf power and prime-power weight, while affording adequate neutron and gamma production and data characteristics for discrimination tests.

Operational guidelines were recommended that provide redundancy; the flexibility provided by the use of the shuttle and its data system; a conservative, three free-flyer system of the NPB, target, and detector; a fully automated NPB to minimize shuttle-crew operational involvement but with manual override; and recovery of the accelerator platform.

Boresighting of the beam with the target is to be provided, with enough electromagnetic beam deflection

TABLE I
RECOMMENDED EXPERIMENT PARAMETERS

Orbit	320 km circular (320 x 150 km elliptical)
Inclination	28.5°
Accelerator Particle	H^-
Output energy	50 MeV (nominal)
Accelerator beam current (H^-)	100 mA
Output beam current (H^0)	>45 mA
Output beam divergence (H^0)	25 µrad (θ/2) rms
Duty factor	0.1%
Beam pulse width (variable)	30 to 300 µs
Pulse repetition rate	Consistent with 0.1% duty factor
Output beam emittance (H^-)	0.02 π cm•mrad (nominal)
Operating frequency	425 MHz (nominal)
Operating temperature	Not cryogenic, nominal room temperature
Temperature stability	0.5°F (about set point)
Configuration	180° bend with design compatible with hinge in DTL
Size	Basic accelerator design compatible with single shuttle launch
Ion source	Modified Dudnikov, 100 keV
RFQ	Loop coupled, 2 MeV
DTL	First tank—ramped gradient, 2 to 4.4 MV/m Remaining tanks—constant gradient, 4.4 MV/m Hinged section to fit into shuttle bay
Beam magnetic optics	25-cm-diam samarium-cobalt permanent magnets with small electromagnet trimmers
Neutralizer	25-cm-diam ring jet, gas-flow system
Beam sensing	Wire shadow
Radio-frequency power	Solid state or klystrode
Control system	Highly automated distributed computer

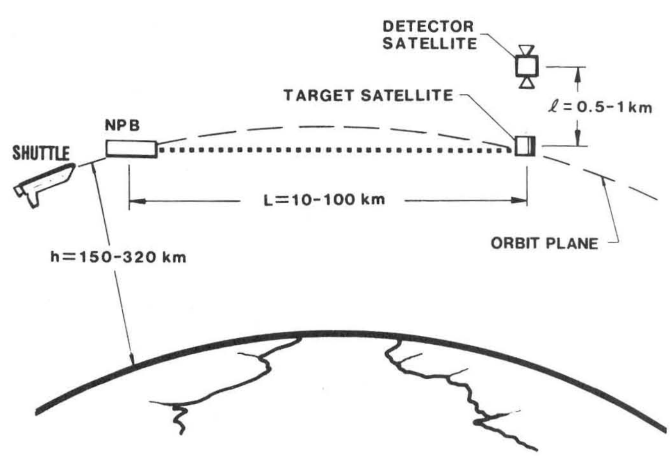

Fig. 2. NPB ISE experiment configuration.

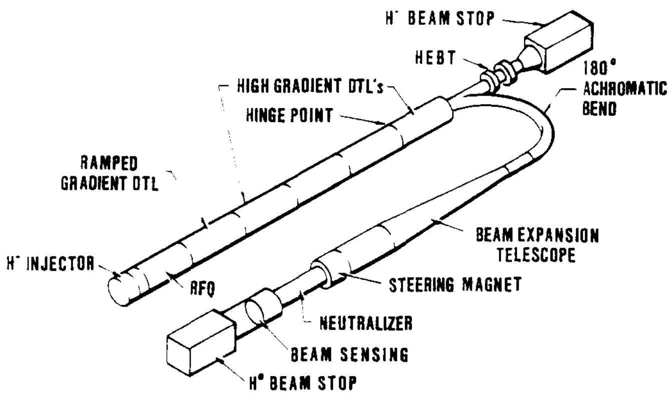

Fig. 3. Outline of 50-MeV NPB device.

for initial acquisition, after which the system should be able to maintain contact without target feedback.

The recommended design parameters for the NPB platform are outlined in Table I. The flight-article design specification is tightly coupled with the Los Alamos GTA; the only significant differences are space qualification and support systems—for example, rf power, high voltage, and vacuum—in which alternate designs will be used for reasons of economy or short-term availability.

The ion source determines the beam brightness, which can only be preserved or diluted in the rest of the machine. The Dudnikov H^- source is the only source with adequate performance for the first ISE; R&D on other sources, particularly those that might avoid the operational difficulties of cesium, is part of the longer range program. A difficult challenge associated with the ion source is to make control of it completely automatic.

The radio-frequency quadrupole (RFQ) preaccelerator will be loop coupled, with azimuthal coupling rings for transverse stabilization and possibly with longitudinal stabilization as well. Thermal and fabrication options are also under intensive investigation, as covered by numerous papers at this meeting.

In the drift-tube linac (DTL) section, the shuttle's length constraint argues for a high accelerating gradient, but the allowable gradient is practically limited because of the need to maintain good beam quality (low emittance), sparking limits on the peak-surface rf fields, and the requirement for more rf power at higher gradient. Beam-dynamics studies showed that emittance could be preserved by starting with a gradient of around 2 MeV/m and ramping up by about 3% per cell to about 5 MeV/m, which is consistent with the other constraints. An unreasonably high gradient of about 7 MeV/m would be required to fit a single-section 50-MeV accelerator system in the shuttle bay; therefore the machine will be hinged, stowed folded, and erected in space. Considerable work has been completed on the mechanical design of the drift-tubes, permanent-magnet quadrupoles, and other components of the DTL. The accelerator will be designed for 5% duty factor, in anticipation of longer term requirements, but will be operated at 0.1% for the ISE.

The rf power system required for an NPB device has received almost no attention to date, in spite of the fact that it forms the major part of the system weight. Since the time that radar systems turned toward phased arrays, little development of compact, high-power, high-efficiency rf systems has occurred. Work is beginning to close this gap, but there is much to be done. Ultimately, several hundred megawatts of cw or long-pulse power will be required. The present ISE requires 14 MW of peak rf power at 0.1% duty factor, giving 14 kW average. The space shuttle has redundant fuel cells that can provide adequate prime power.

We are interested in frequencies around 400 MHZ, with high efficiency, low volume ratio (W/Cm^3), weight ratio (W/kg), and cost ratio ($/W). Extant klystron systems have modest efficiencies around 55%, unacceptable weight and volume ratios, and require high drive voltage. Gridded tubes have low gain, resulting in overall efficiencies around 50%, and extrapolate poorly to future requirements because of plate dissipation limitations. Two new sources are under study; at present, their differences are within the errors of the system estimates. The first is solid state, exemplified by the Westinghouse SPS-40 radar system, in which ten 380-W transistor circuits are combined into 2.5-kW modules and combined again to produce 25 kW. Pulse lengths are only 60 µs, at 5% duty factor. Recently a 2-kW, 1-ms, 10% duty, 80% efficient long-pulse module was demonstrated that could be combined in a 500-kW amplifier module with prime power-to-rf efficiency of about 55%. The weight ratio at present is about 1320 W/kg with about 2200 W/kg on the horizon. The Eimac/Varian klystrode is another possibility, more compact than a klystron because it uses a gridded interaction region with a klystron-like output cavity and collector. Tubes are available for 25-kW, cw, UHF-TV service and should scale to a few hundred kilowatts cw. Contrary to solid state, where volume and weight scale directly with power, the klystrode tube size would increase about 20% as the power is doubled. The dc-to-rf efficiency of the klystrode is about 70%, but the gain of about 23 dB still requires a high-power driver. Magnetrons and crossed-field devices are not sufficiently phase stable for accelerator service, although some very recent work may have an impact on this aspect.

The 50-MeV-output optics system prepares the beam for neutralization and propagation. Its components include

- a debunching section to reduce the beam's energy spread, which lessens the effect of chromatic (energy-dependent) aberrations in the lens elements;
- perhaps a rebuncher to introduce time-dependent effects that would exploit rate-dependent effects at the target;
- 180° bend to allow the system to be folded for compactness;
- a beam-expanding telescope in which beam divergence is reduced at the expense of beam size to the point where spherical and higher order aberrations in the lenses preclude further expansion; and
- beam steering elements.

The first ISE may not require a debuncher, or a 180° bend if the system were erected straight in space. Weight restrictions also indicate that permanent-magnet lenses be used, whereas later, higher performance systems may use electromagnets. The presence of space charge makes the output optics system nonlinear, severely complicating the design and optimization procedure; therefore, this area is a high-priority subject at present.

The neutralizer, where the H^- particles are converted to H^0 for propagation, needs to be efficient, simple, and reliable and needs to preserve the beam quality as much as possible. A thin, solid foil is the most attractive candidate because of its simplicity; but at present, foils of adequate size cannot be produced, and the time needed for development probably is long. Therefore, stripping-in a thin gas medium has been selected; a mature technology is associated with gas-flow systems, and it appears that a system, although complicated, could be scaled to meet the ISE requirement. The baseline design uses argon in a ring-source design with a 25-cm aperture.

The automatic pointing and tracking (ATP) and beam-sensing systems introduce elements to the accelerator system that can utilize many of the techniques of experimental particle physics. The pointing accuracy requirements for ATP will require active measurement and control of any jitter; thus, engineering control of vibrations or other jitter-producing mechanisms, as well as a method to actively control jitter, will be stressed in the design of these machines.

The instrumentation-and-control aspects of an NPB platform offer a challenge comparable to that accepted in the early 1960s, when LAMPF was the first major accelerator installation to include computer control as a primary objective of the initial design. Now we must largely remove the human operator and provide remote, rapid-start operation. For some of the subsystems (such as the ion source) and for the overall system, the controls aspects constitute a major program area.

The ISE is clearly an ambitious R&D program that will focus a number of new developments in linac technology, changing in basic ways how linacs are built and operated. Briefly reviewing, development is required in controlled ion sources, ramped-gradient DTLs, lightweight, high-power accelerator structures, hinged construction, multiple rf drive, higher efficiency rf systems with better weight and volume ratios, permanent-magnet optics, neutralizers, ATP and beam sensing, and automatic control.

Several other important technology-base program areas are proceeding in parallel with the ISE and its associated GTA. The accelerator test stand (ATS) at Los Alamos continues as the focal point. Figure 4 shows the system now installed: 100-keV ion source, RFQ to 2 MeV, and DTL to 5 MeV. A ramped-gradient DTL will also be tested here. Information on this work is presented elsewhere at this meeting. A highlight of the ATS diagnostic system is the new longitudinal emittance measurement, done by time-sliced laser stripping of the accelerated beam and time-of-flight measurement on the resulting H^0 beamlet (Fig. 5). The technique will eventualy be extended to measure the full six-dimensional phase-space density distribution. Other ATS activities cover ion-source development of several types, neutralization studies, and rf field-limit tests.

Longer term activities, many in collaboration with other laboratories in this and other countries, are looking at advanced methods for multiple or funneled beams, cw linacs, tests of beam-sensing methods at several energies, advanced neutralizers, and development of discrimination methods and sensors.

An important near-term first test of an accelerator system in space will be accomplished in the BEAR (Beam Experiment Aboard Rocket) program. The payload segment,[3] shown in Fig. 6, will be launched in an Aries rocket and will spend about 200 s above 180-km altitude. The total accelerator package is 1.12 m in diameter and 3.66 m long. The accelerator will provide about 10-mA H^0 beam at 1 MeV. The flight objective is to demonstrate operation of the NPB accelerator system, project a beam that interacts with the local environment, and measure aspects of beam propagation, spacecraft charging, and system interactions.

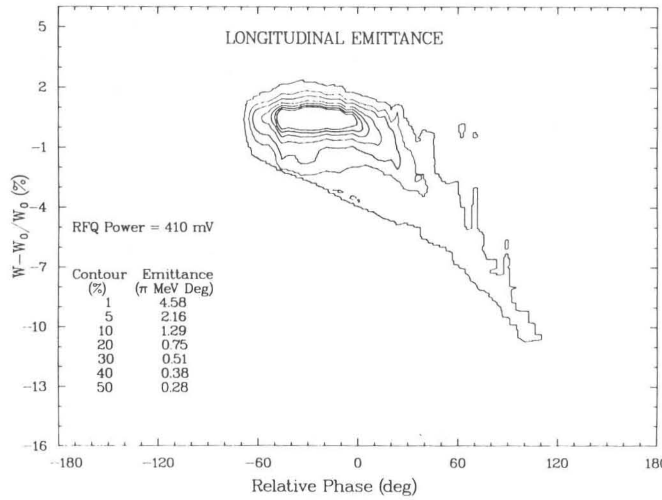

Fig. 5. Longitudinal emittance measurement performed by time-sliced laser stripping.

Free Electron Laser[4,5]

Ground-based laser defensive systems must operate at wavelengths in the visible or near-infrared spectrum where atmospheric transmission is possible. FELs can operate at any wavelength from microwave to far ultraviolet because the electron beams that provide the pump energy are operating in a vacuum and therefore are not restricted to operate on molecular transitions. Moreover, FELs are easily tunable to adapt to atmospheric conditions. The electron linac driver is also well suited to

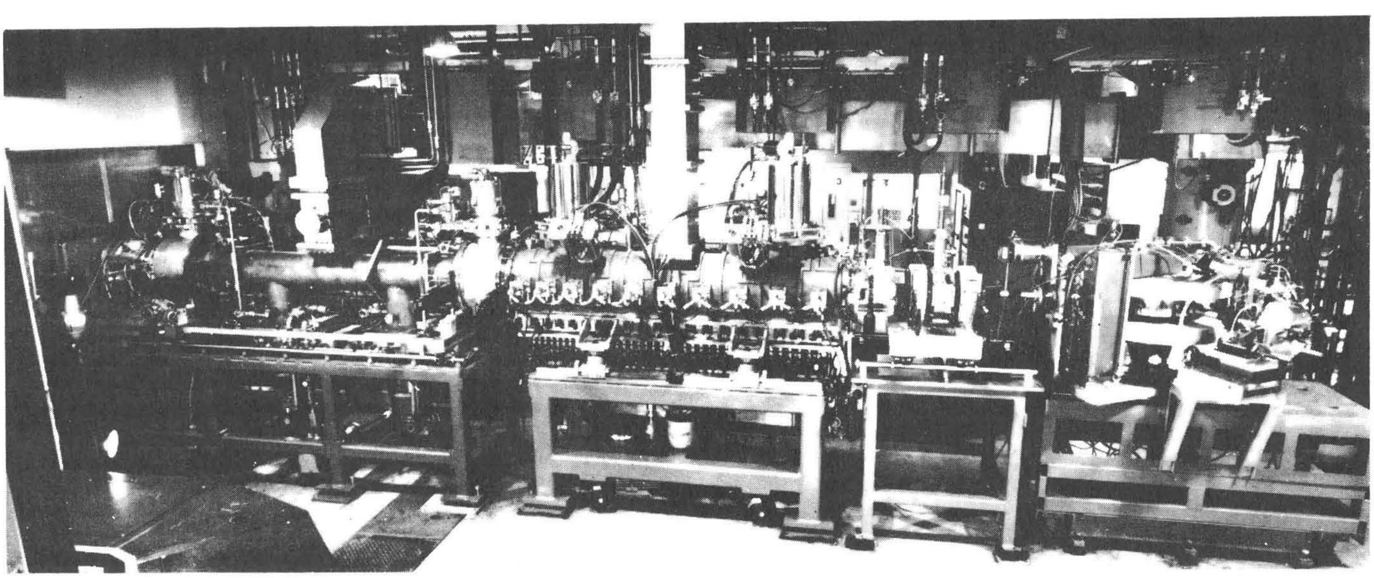

Fig. 4. NPB Accelerator Test Stand.

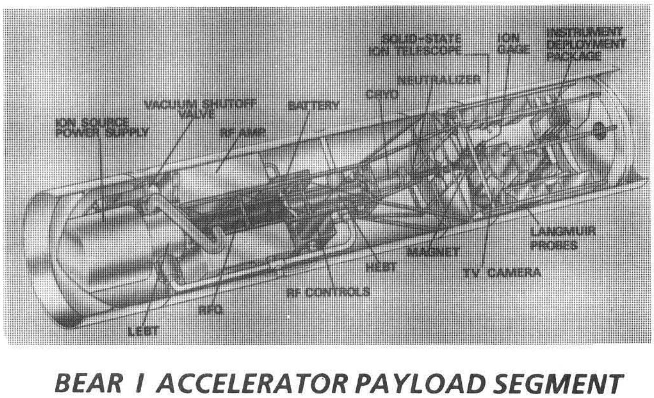

Fig. 6. BEAR payload segment.

high-power operation because the waste heat, residing in the electron beam, passes instantly out of the laser; the laser mirrors, however, m ust deal with the power in the light beam. FELs appear capable of overall system efficiencies in excess of 10%. There are two main approaches to such high-power FELs, based on rf or induction linac drivers. The IL FEL must operate as an efficient single-pass amplifier. The rf linac FEL operates as an oscillator with a lower electron energy to light-conversion efficiency but with an enhanced overall efficiency achieved by recovering energy from the spent electron beam.

Basic performance requirements on the rf or IL electron-beam driver are shown in terms of peak brightness and current in Fig. 7. It is not possible to make all the necessary comparisons on one graph, but peak quantities are useful in comparing physics issues. The operating boundary lines shown are for linac energies that would be used for roughly equivalent high-power system designs. With the rf linac FEL oscillators, the brightness and current required for lasing at a given wavelength are directly related. The operating region for an IL FEL amplifier is doubly bounded in the upper right corner because high current is required to trap the optical beam in a long wiggler, whereas high brightness is required to trap the electrons in the pondermotive buckets and decelerate them efficiently. The rf linac research is concentrating on bright photocathode sources and careful control of unwanted deflecting "beam-breakup" modes in the accelerator structures; theory indicates that the design goal should be possible at average electron-beam currents needed for high power (1 A). ILs face a severe challenge in attaining enough brightness; source performance is improving but will have to be maintained through the linac. Beam breakup in the ATA has been suppressed by laser guiding of the electron beam. With stronger magnetic-guide fields, IL FELs may avoid the complications of laser guiding.

In the FEL itself, both approaches are subject to synchrotron instabilities, apparently not serious at present but of more concern in achieving high efficiencies at shorter wavelengths. It is clear that the bunch-current densities in the rf device require care to avoid wakefield effects that can degrade brightness. The optical quality of the rf device has been demonstrated both experimentally and theoretically to be nearly perfect, a consequence of operation as an oscillator. The IL device requires focusing of the optical beam through a long wiggler by using the index of refraction of the electron beam to achieve the high efficiency; this also means that the optical beam quality may be dependent on the electron beam properties, which may be difficult to control uniformly.

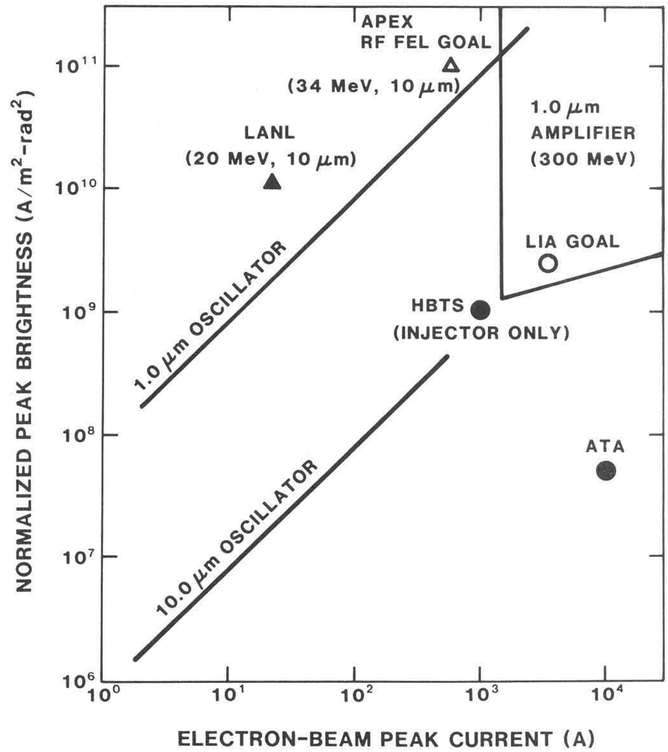

Fig. 7. Peak brightness and current requirements for rf FEL oscillators and induction linac FEL amplifiers. The ATA and LANL points represent linac output. The IL High Brightness Test Stand (HBTS) point is at the injector and the brightness would have to be maintained through the matching to the accelerator and subsequent acceleration.

The engineering issues are equally complex. High average power, cw electron linacs already exist; although such ILs have not been built, it appears that new magnetic-modulator technology should support high average power. ILs have pulse-length restrictions from the ferrite cores of the induction modules and relatively lower accelerating voltage per meter because of insulator voltage limits. Optical component damage is a major concern for both; this determines how long the optical system must be. The IL FEL, being an amplifier, requires an input laser and laser light for guiding the e-beam in the linac; these are not available today at the required high average power. If both rf and induction FELs perform as required at equivalent average power, the rf device would be considerably more compact; that is, the linac, wiggler, and optical system would all be about a factor of 10 shorter for the rf device compared to the IL device. For ground-based systems, the size consideration may be mainly one of cost, which is proportional to size, but for a space-based system, the difference is critical.

The Los Alamos FEL experiment has been configured into the third and final stage of the R&D program designed to demonstrate proof of principle for all the fundamental FEL physics issues before scaling to high power and short wavelength. The system, outlined in Fig. 8, uses a 20-MeV linac to drive a 10-μm wavelength FEL. The objectives are to improve the operating parameters, to demonstrate the rf energy-recovery technique, and to continue FEL physics studies. The first has been achieved; the linac performance is as indicated in Fig. 7, and a tapered-wiggler FEL, oscillator configuration has

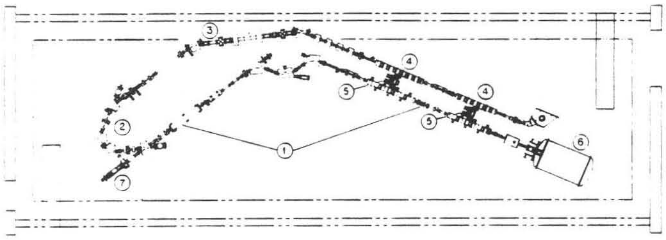

Fig. 8. Los Alamos rf-linac-driven FEL energy-recovery experiment layout: (1), OSX accelerator and FEL operating at two-fold increase in peak current; (2), isochronous 180° bend on translation table; (3), isochronous 60° bend; (4), two 1.8-m decelerator (energy-recovery) sections; (5), two variable rf bridge couplers; (6), beam dump for 2- to 3-MeV beam; (7), 20-MeV diagnostics.

achieved 2% extraction efficiency—the highest performance yet from an FEL operating above the microwave spectrum and on principles scalable to high power and short wavelength. Optical damage to the dielectric mirrors of the optical resonator limited operation to a factor of 2 below the design point; tests with copper optics are planned that should raise both the power level and the extraction efficiency.

The electron beam still has most of its power and its microbunch structure after exiting the FEL, but its energy spread is too great to allow recirculation through the wiggler. Electrical recovery of the beam power could improve the overall system efficiency by more than a factor of 2 in high-power, high-current systems where the beam power is large compared to the structure losses. The best way to recover the kinetic energy is to decelerate the beam in the same type of rf-linac structure, producing rf power that is used to accelerate new beam. A conversion efficiency greater than 99% appears possible for this process. The experiment will decelerate in a separate structure, with bridge couplers to resonantly share recovered power with the main accelerator.

The FEL physics studies primarily address enhanced efficiency, through better understanding of the production and suppression of transverse wakefield and synchrotron sideband effects, and the possibilities afforded by using the electrons to provide optical beam bending and focusing. Wiggler design improvements will be a major effort. Another major-program element is the bright-photocathode injector development, where bunches of electrons are produced at the correct time for direct capture into rf accelerating fields, as shown in Fig. 9. This status of that work is described in another paper at this conference.[6]

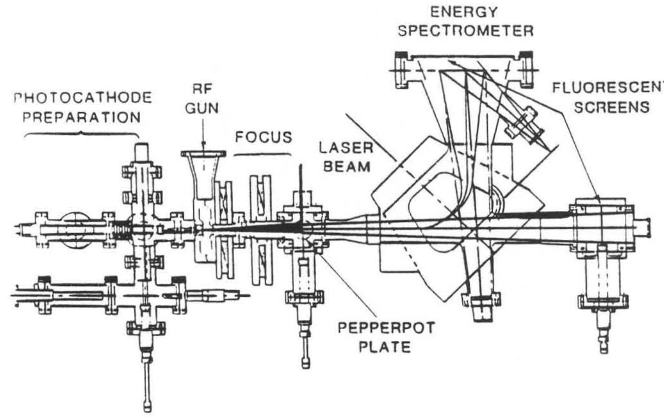

Fig. 9. Laser-driven photocathode and rf-cavity injector-development experiment at Los Alamos.

Acknowledgment

The programs discussed in this paper are the work of a large number of people, work hardly done justice to by this very brief discussion. The many discussions are gratefully acknowledged.

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