Accelerator Requirements for Strategic Defense

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Abstract

Directed energy applications require accelerators with high brightness and large gradients to minimize size and weight for space systems. Several major directed energy applications are based upon accelerator technology. The radio-frequency linear accelerator is the basis for both space-based neutral particle beam (NPB) and free electron laser (FEL) devices. The high peak current of the induction linac has made it a leading candidate for ground based free electron laser applications.

Introduction

The objective of this paper is to describe the requirements of accelerator programs for strategic defense and to discuss the progress made in achieving them. I will use reference 1 as a starting point in describing recent progress.

Neutral Particle Beam Technology

In a neutral particle beam system, negative ions are accelerated, magnetically pointed at the target, and then stripped to provide an electrically neutral beam for space propagation with minimum divergence. The main elements in such a system are the radio-frequency (RF) and prime power, the negative ion source, the radio-frequency quadrupole (injector), the drift tube linear accelerator (DTL), magnetic optics, beam sensing system, and neutralizer.

The key to minimizing divergence and thereby maximizing power (or current density) per unit solid angle [i.e. brightness] is to create the negative ions with low emittance, to preserve the emittance throughout the accelerator, and to have the lowest possible scattering induced divergence in the neutralization process. The emittance of the neutral particle beam is determined by the negative ion source and subsequent accelerator components and is proportional to the transverse temperature of the beam. In thermodynamic terms, the emittance can be related to the entropy which can only increase or, with proper design, be maintained as the beam is accelerated.

In comparing the brightness of an NPB beam to a laser, the emittance is analagous to the wavelength of light. Just as the wavelength divided by the final optical beam diameter determines diffraction limited divergence for a laser, the emittance divided by the final magnetic optics diameter approximately determines the minimum divergence for the NPB. Scattering in the neutralizer is the other major factor in limiting brightness.

Because NPB systems are designed for space applications, another important requirement is for high gradient accelerators to provide compactness and to minimize weight. High efficiency is even more critical for space applications to minimize both power supply weight and cooling requirements. Such concerns have led to a recent examination of both cryogenic and superconducting accelerators.

A Summary of NPB Progress

In November, I described NPB progress at the Denton Accelerator Applications Conference. [1] These results are summarized below:

The Lawrence Berkeley Laboratory demonstrated that lanthanum hexaboride cathodes can operate with high current density in both cesium free surface discharge and volume negative ion sources. For surface discharge sources, the LaB6 takes the place of the low work function cesium on the cathode. They concluded that even surface sources have substantial volume negative ion production.

A volume negative ion source developed by Culham Laboratory operated continuously and reproducibly with more than 135 mA and good beam quality.

The Accelerator Test Stand at Los Alamos, consisting of a pulsed surface discharge (Dudnikov) negative ion source, a 2 MV/m radio-frequency quadrupole (RFQ), and a 5 MV/m drift tube linac, produced a 5 MeV, 100 mA beam. More than 80% of the beam produced by the negative ion source was transported through to the end of the 425 MHz accelerator.

The Fusion Materials Irradiation Test Facility at LANL consisting of a positive ion source and 80 MHz RFQ, accelerated 50 mA of H2+ (substituting for deuterons to minimize radioactivity) to 2 MeV.

Solid state transistor RF power modules developed by Westinghouse for radar applications were modified to minimize weight and to drive an accelerator load. These solid state power supplies, developed for the 1 MeV "BEAR" space experiment, had achieved a specific power of 0.97 grams/watt.

Recent NPB Progress

Since November, several important developments have occurred:

At Los Alamos, the 4X surface discharge source produced a 250 mA beam with an emittance of .014 x .025 pi cm-mrad. This brightness of 144 A/(cm-mrad)2 is the highest reported to date. The duty factor was 0.5% although this type of source has operated at 6%. The improvement responsible for this increase (3X higher than the small angle Dudnikov source now operating on the Los Alamos Accelerator Test Stand) was the development of an optimized slit extractor. [2]

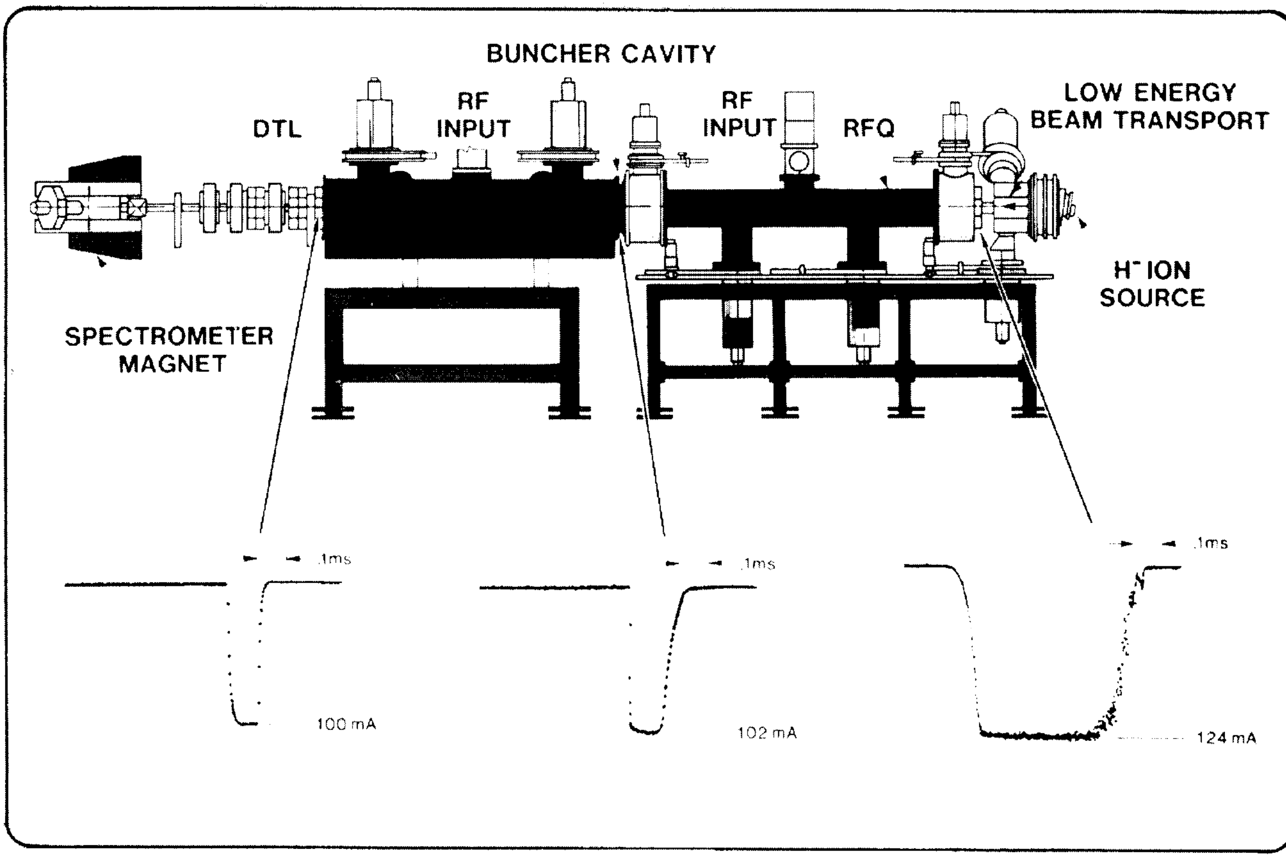

Figure 1. The Accelerator Test Stand at Los Alamos National Laboratory (LANL). The current traces indicate both the bunching of the ion source beam in the RFQ and the high transport efficiency through the RFQ and DTL.

Emittance measurements were completed on the Culham volume ion source. Operating at 100% duty factor with 30 second pulses, this source produced more than 135 mA with an emittance of .025 pi cm-mrad in both dimensions, a brightness of 15 A/(cm-mrad)2. An important recent discovery by Holmes was that the deflection of negative ions by the magnetic field in the extraction region was a major source of emittance growth. This spread in transverse velocity arises because the negative ions are generated at various distances from the extraction plane and their magnetic deflections differ in a stochastic fashion. [3]

At the Lawrence Berkeley Laboratory a pulsed volume ion source produced 120 mA using multiple apertures for extraction. They found that ion current scaled less than linearly with the diameter of the output aperture, and that for apertures larger than a few millimeters, the noise in the ion current increased considerably. By using an array of 55-90 1 mm output apertures, they found linear scaling with the number of these holes, and no emittance growth in comparison to a single one. [4]

The first pulsed negative ion source designed for space applications (the "BEAR" 1 MeV rocket experiment) was successfully operated under computer control by Los Alamos. This surface discharge source features an improved thermal design that permits quick turn-on and shutdown without the need for a dc discharge conditioning (with the attendant high gas load). [5]

Carbon foil neutralizers have been developed and tested at energies up to 50 MeV. The foil neutralizer is simple to construct and experiments have demonstrated that these foils are sufficiently durable for the NPB application. Large diameter graphite foils have yielded a neutralization efficiency of more than 50%.

The BEAR experiment will demonstrate the ability of an NPB system consisting of RF power, pulsed surface discharge negative ion source, RFQ, and gas cell neutralizer to operate in space. BEAR will operate for more than 400 seconds at altitudes of more than 200 km with a 1 MeV, pulsed H beam. In November, I reported than the solid state RF power modules (silicon bipolar transistors operatng at 425 Mhz) for BEAR had achieved 0.97 grams/watt. Further improvements in module design have improved the specific power to 0.3 grams/watt for a low duty factor system.

Silicon field effect transistors and static induction transistors are also promising for higher duty factors. Gallium arsenide metal semiconductor field effect transistors are the solid state device of choice for frequencies above 3 GHz because of the substantially higher electron mobilities. [6].

These advances are summarized in Figure 2.

Free Electron Laser (FEL) Technology and Requirements

FELs require high brightness electron beams to have high gains. This brightness requirement increases as the wavelength of the FEL decreases. In an FEL, electrons are bunched by the wiggler at the optical period. These electron bunches travel along almost in synchronism with the light wave. Because the electrons are traveling slightly slower than c in the axial direction because of their oscillatory longer path, they slip behind one optical period per wiggler wavelength relative to the light beam. The distribution in axial velocities of the electron bunch causes the bunch to expand and fall behind the light wave. For a strong interaction this spread in axial velocity must be minimized. Because the change in axial velocity is proportional to the transverse velocity of the electrons, the emittance must be minimized. The shorter the optical wavelength, the less the axial velocity spread must be. That is,

$$\frac{\Delta V_z}{c} << \lambda_s/\ell$$

where ΔV_z is the axial velocity spread, is the optical period and ℓ is the e folding length for power amplification. This limitation on the transverse velocity of the beam, leading to axial velocity spread, combined with the maximum beam radius (usually lambda wiggler over 20 or less) allowable because of wiggler magnetic field variations places an upper bound on emittance. [7,8]

In practice, this analysis means that for the Lawrence Livermore National Laboratory (LLNL) experiment on FEL amplifiers using the 4 MeV Experimental Test Accelerator which demonstrated high efficiency (>40% using a tapered wiggler) in the microwave region (0.86 cm wavelength), a brightness of 2x10(4) amps/(cm-rad)2 was required. [9] The present Paladin experiments at 10.6 microns require an order of magnitude better brightness [7].

High current induction linac FELs which produce high gain in amplifier experiments may be limited to ground-based applications because of the weight of the ferrite accelerators cores. However, RF linac FELs are promising for both ground and space-based applications. For space applications, these RF linacs must have high gradients for compactness. Superconducting cavities provide gradients up to 10 MeV/m (for multiple cavities with higher gradients for single cavities) and have a substantially higher current threshold for the onset of the beam breakup instability. [10]

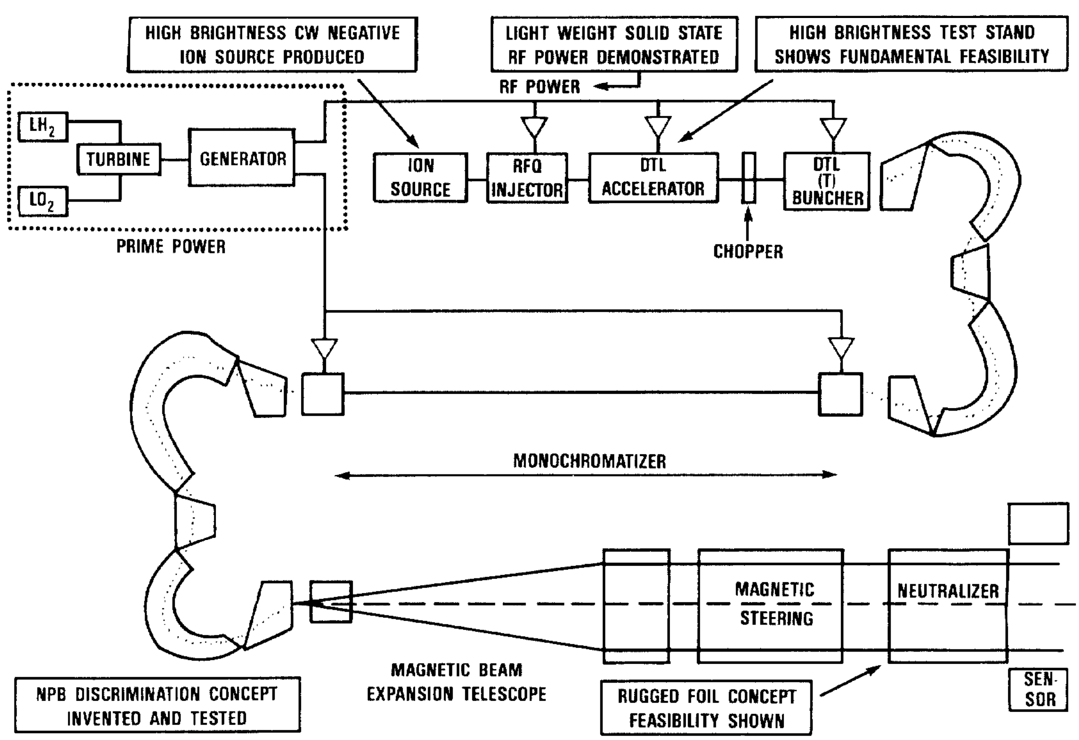

Figure 2. This NPB block diagram shows significant progress in RF power, ion sources, emittance preservation, and foil neutralizers.

A Summary of Progress on Electron Accelerators for FELs

In November, I reported on several important accomplishments in free electron laser technology:

The high brightness test stand at LLNL achieved a brightness of more than 10[6] A/(cm rad)2 at 1.5 MV. Repetition rates above 350 Hz were achieved at lower brightnesses with 1 kA peak current.

At LLNL, laser ionization channels in low pressure gas were used to guide an intense electron beam more than 90 meters including 60 m inside the 50 MeV accelerator and an additional 30 m beyond. A transport efficiency of more than 90% was achieved with electron beam transverse motion reduced to less than a millimeter at the end of the accelerator.

Experiments at Sandia Laboratories showed that a similar technique employing low energy electron beams to make curved ionization channels could be used to make a high current recirculating accelerator.

Progress in superconducting technology at Cornell University for the Continuous Electron Beam Accelerator Facility including improved materials (better thermal conductivity) and manufacturing methods, better rf coupling methods, and control of instabilities resulted in cavity Q's of 5x10(9) and gradients of up to 8 MV/m at 1500 MHz. For single cell cavities, gradients of 31 MV/m have been achieved. [11]

Energy recovery experiments with room temperature (LANL) and superconducting FELs (TRW-Stanford) demonstrated that 75% to 90% of the electron beam after passing through the wiggler could be converted into rf energy.

Recent FEL Accelerator Progress

LANL has extended their results with photocathodes to peak currents of 390 A in a 50 ps pulse. In comparison to the conventional approach of using a thermionic cathode of limited brightness followed by a bunching process which increases peak current, the photocathode approach relies upon the rapid photoemission of electrons to produce very high peak currents and brightness at high repetition rates.

A frequency doubled Nd-YAG laser at 532 nm was incident on a cesium antimonide photocathode. This mode-locked laser produces pulse trains at a microscopic repetition rate of 50 to 120 Mhz. Cs3Sb was chosen over gallium arsenide because the former is less sensitive to contamination and has a positive electron affinity which results in the more rapid emission of the photoelectrons. Brightnesses of more than 10(10) amps/(m-rad)2 have been reported by LANL. [12]

First light has been reported this year in several important FEL experiments. In the 50 MeV Paladin experiment at the Lawrence Livermore National Lab, gain has been observed in a 10.6 micron amplifier experiment [7].

This result was made possible by achieving several stressing accelerator requirements:

- regulation of the electron energy to 0.25%
- reducing electron beam transverse motion at the end of the accelerator to 10% of the (1 mm) electron beam radius
- magnetic alignment to one part in 10,000
- improvement of the ATA injector brightness to 2x10(5)

On a separate prototype injector for a higher energy system, advances in magnetic compression switching technology and injector brightness have resulted in a 0.75 kA/0.8 MeV injector operated at kilohertz repetition rates accelerated through a 2 MeV/20 cell block accelerator with an output brightness of 1.3x10(6) A/(cm-rad)2. [7]

The first lasing of the shortest wavelength FEL powered by a linac was reported in February by a group from TRW and Stanford. Using the Stanford superconducting accelerator operating at 115 Mev, lasing at 525 nm was achieved with both tapered and untapered 5 m wigglers. The acceleraor produced 3A peak current with a 3 ps pulse every 84 ns. Macropulse length ranged from 1 to 5 milliseconds with a 40 Hz rep rate.

Perhaps the most significant parameter, aside from the short wavelength, is the low energy spread -- 0.15% in these experiments as compared with values of about 10 times higher for the LANL and Boeing room temperature linacs. The is a key feature of superconducting accelerators. The high duty factor operation makes possible precise tuning using immediate and direct feedback. The TRW-Stanford group points out that it is signficiant that the first FEL used a superconducting accelerator, the first tapered wiggler result employed an SC accelerator, and now the first visible FEL using a linac uses a superconducting accelerator. [13,8]

LANL recent demonstrated the ability to guide multiple pulses using a laser-formed ionization channel. Two 5 ns, 750 A, 30 MeV pulses separated by 20 ns were transported over 13.5 m. Using the Phermex standing wave rf linac and a KrF excimer laser to form the ion channel, good transport efficiency was obtained. The beam width and current losses were less than 10% over this distance. [14]

Sandia National Laboratory has continued to develop the concept of electron beam guiding in the ion focused regime for recirculating accelerators. In November, they had used a low energy electron beam to create a curved ionizational channel which they used to guide an intense electron beam around 270 degrees of bending with good transport efficiency.

They have now extended these results to guiding a 9 kA, 2.5 MeV around 360 degrees, with 5 kA transported to the 1 MeV "ET2" induction linac 1 MeV acceleration cavity. [15]

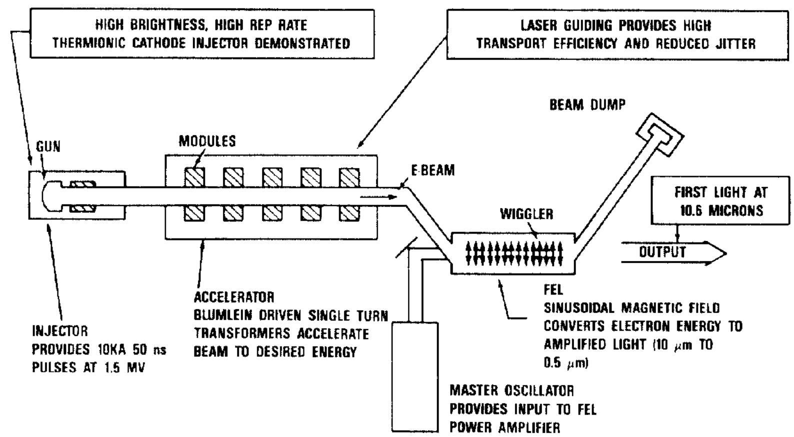

Figure 3a.

RECENT PROGRESS FOR INDUCTION LINAC FEL

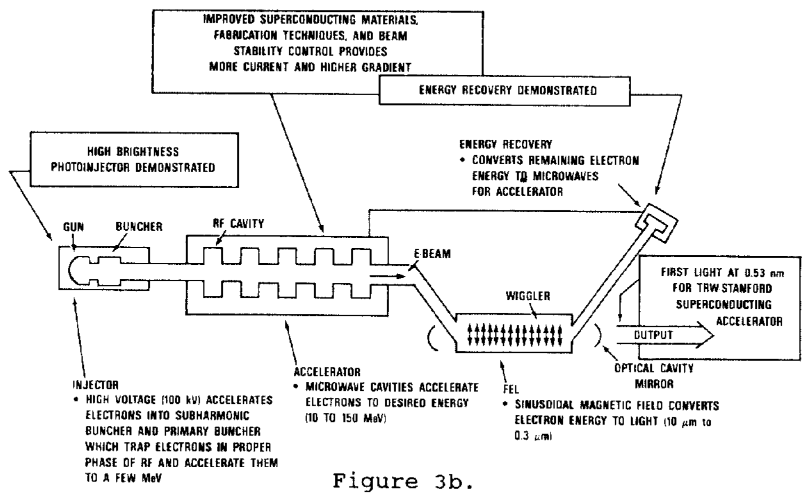

Figure 3b.

RECENT PROGRESS FOR RF LINAC FEL

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