Airborne Tactical Free-Electron Laser

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ABSTRACT

The goal of 100 kilowatts (kW) of directed energy from an airborne tactical platform has proved challenging due to the size and weight of most of the options that have been considered. However, recent advances in Free-Electron Lasers appear to offer a solution along with significant tactical advantages: a nearly unlimited magazine, time structures for periods from milliseconds to hours, radar like functionality, and the choice of the wavelength of light that best meets mission requirements.

For an Airborne Tactical Free-Electron Laser (ATFEL) on a platforms such as a Lockheed C-130J-30 and airships, the two most challenging requirements, weight and size, can be met by generating the light at a higher harmonic, aggressively managing magnet weights, managing cryogenic heat loads using recent SRF R&D results, and using FEL super compact design concepts that greatly reduce the number of components.

The initial R&D roadmap for achieving an ATFEL is provided in this paper. Performing this R&D is expected to further reduce the weight, size and power requirements for the FELs the Navy is currently developing for shipboard applications, as well as providing performance enhancements for the strategic airborne MW class FELs. The 100 kW ATFEL with its tactical advantages may prove sufficiently attractive for early advancement in the queue of deployed FELs.

Keywords: Free-electron laser, FEL, laser, airborne, tactical, megawatt, airship, relay mirror, submarine

1. INTRODUCTION

Airborne tactical directed energy becomes very useful when 100 kW class beams are developed on tactical platforms such as a Lockheed C-130J-30 and airships. Achieving an ATFEL requires tight coupling of the FEL with the airplane while minimizing weight, size, electric power and cooling requirements. Figure 1 shows a top view of an FEL in the cargo bay of a C-130J-30. The directed energy beam will come out below the aircraft.

A C-130J-30 can carry 46,812 pounds, though its normal payload is somewhat less at 38,812 pounds. It is important to get the weight significantly below the 46,812 pound level so that other tactical systems can be integrated into the platform and the aircraft operates closer to its normal payload.

In working out the concepts for an ATFEL the following parameters have been selected:

• The initial directed energy power operates continuously at 100 kW.
• A C-130J-30 will be used as the example tactical aircraft.

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The FEL and all of its subsystems will fit into the standard cargo bay except for an Auxiliary Power Unit (APU) and the beam director mirror system. The output wavelength will be taken as in the region of 1.625 microns, a relatively eye safe wavelength that is useful in both maritime and non-maritime environments. The beam directional mirror system will be sized for an effective range of 10 - 20 kilometers.

2. SUPER COMPACT FEL

A compact FEL for shipboard applications has been designed for the Navy. To meet the weight and size requirements for an ATFEL, the design must be further compacted into a super compact design.

2.1 Jefferson Lab FEL

The predecessor to the compact FEL concept is the largely Navy funded Jefferson Lab FEL that is a spinoff of the technologies developed to accomplish the U.S. Department of Energy Office of Science’s nuclear physics mission at the Lab: performing fundamental research into the nature of matter at the quark and gluon level. Significant advances in Superconducting Radio Frequency (SRF) and Energy Recovering Linac (ERL) technologies enabled the development of the world’s highest-average-power FEL which has achieved 14.2 kW at 1.6 microns.

2.2 Compact FEL

While the Jefferson Lab FEL has been designed as a research device with an expanded layout for design studies, a Navy goal is to achieve a compact device that can be placed on a variety of ships. Using advanced accelerator physics optics concepts, this goal has been met at the design level. The concepts for using this same design have been worked out for an airborne MW class FEL on a strategic platform such as a Boeing 747. In the compact FEL for an aircraft there would be three cryomodules, one each for the injector, accelerator and beam stop. The electron beam energy collected in the beam stop as RF is fed back to the injector, and the electron beam energy collected as DC is fed to the gun high voltage system. The photon beam is produced using the fundamental mode in the compact FEL’s wiggler.

2.3 Light Weight Super Compact FELs

Two super compact FEL concepts are considered in this paper and referred to as Concept 1 and Concept 2. The key ideas are to achieve the desired reduction in weight and size by integrating the cryogenic elements into a single cryomodule, operating the wiggler in third harmonic mode, and operating the SRF cavities at 1.6 K.

2.3.1 Electron Beam Energy, 3rd Harmonic Operation, and Electron Beam

The electron beam energy required to produce a given wavelength of directed energy light depends on four parameters:

- The geometry of the magnetic field in the wiggler – Two geometries are typically used, planar and helical.
- The strength of the magnetic field in the wiggler usually expressed as a dimensionless parameter K – For FELs of interest, K typically ranges from 1 - 2. Higher Ks result in higher beam energies being required.
- The period of the wiggler – Periods of 2 - 3 cm function well for light in the 1 - 2 micron range.
- The harmonic of light being produced – For example, the required electron beam energy is reduced a factor of the square-root of three to achieve a given wavelength of light for an FEL operating in 3rd harmonic mode. The planar wiggler is preferred for generation of harmonic light.

MW class FELs being considered for light in the 1 - 2 micron range will operate with the wiggler in the fundamental mode. These FELs typically plan for electron beam energies in the range of 80 - 110 MeV. This energy range is too high to be able to fit an FEL on an airborne tactical platform. In addition, the weight of the cryoplant would be too great to remove the heat for an accelerator operating in this energy range. These issues are removed by operating the FEL in the 3rd harmonic mode and with the wiggler’s K value set to the lower end of the typical range. For example, an FEL with a planar 2.4 cm wiggler with a K = 1 only requires 36 MeV electron beam energy to produce 1.625 micron light in 3rd harmonic mode.

Typically 1.5 - 2 percent of the FEL’s electron beam energy can be transformed into directed energy light. Taking the 1.5 percent value and the desired 100 kW light out means that the power in the electron beam is 6.7 MW. The electron beam
power is the product of the electron beam energy and electron beam current. It is desirable to keep the current low. It is also desirable to have the electron beam energy high enough to help mitigate electron bunch space charge effects. A reasonable optimization for this discussion is to slightly increase the wiggler period and/or $K$ such that the electron beam energy is 45 MeV. The resultant electron beam current required is slightly less than 150 mA. As a point of reference, currently a 100 mA gun and injector are being constructed at Jefferson Lab and R&D for significantly higher current guns and injectors is underway at several laboratories.

For both Concept 1 and Concept 2 super compact FELs, ERL techniques are used with the single cryomodule for the electron beam all the way to the beam stop resulting in 99 percent of the returning electron beam energy being recovered. Several advantages result:

- For a given peak electron beam energy, the heat load on the system is reduced thereby reducing the weight of the cryogenic Helium Refrigerator.
- The weight of the cryomodules is reduced.
- The system is simpler.

When the electron beam emerges from the accelerator it is in a stream of bunches several picoseconds long in time. The spacing between bunches is determined by the frequency used for the SRF cavities. In general, frequencies from 400 to 800 MHz are optimal for FELs. The higher end of the range may be best for an ATFEL to minimize the weight by keeping the physical size of the cavities to a minimum though frequencies near 500 MHz have other advantages including larger inter cell openings. A frequency of 750 MHz will be used for this paper which results in the electron beam bunches being separated by multiples of 40 cm. With a round trip of 20-24 m in the optical cavities, there will be up to 50-60 independent sub picosecond bunches separated by 1.33 nanoseconds making up the directed energy beam.

### 2.3.2 Super Compact FEL Concept 1

In the Concept 1 FEL shown in Figure 2, the gun, injector, accelerator/linac and beam stop cryomodules/cryounits of the compact design are combined into a single cryomodule. The gun is either a SRF gun (see Figure 3) or possibly a DC gun up until ~0.5 MV that would feed into the first SRF cavity. Beam from the gun acquires full energy in the accelerator, loses ~0.5 MeV in the first portion of the depressed collector, and regains that energy as it leaves the depressed collector. As indicated above, the beam loses 1.5% of its energy in the wiggler to produce the directed energy. As the electron beam passes back through the accelerator, phasing is set so that all of the energy of the beam is directly fed back into the RF except for the ~0.5 MeV that is collected in the depressed collector beam stop. The system operates as an ERL and the accelerating beam acquires more energy than the deaccelerating beam loses to provide energy for the lasing and energy going into the beam stop. Both the returning electron beam and the gun’s photo cathode are slightly offset from the center line such that their transverse currents cancel.

![Figure 2: Concept 1](image-url)
The 150 mA of current stopping in the Depressed Collector beam stop at 0.5 MeV generates 75 kW of DC power. This is used to help drive the Inductive Output Tubes (IOTs) that provide the RF. The total RF power provided to the system is 175 kW, i.e. 100 kW for the directed energy and 75 kW going into the beam stop. Note, in the compact design an independent beam stop must convert a ~7.5 MeV beam to RF to feed back to the injector. Consequently the total RF in that system is many times higher.

Going back to the gun, an independent drive laser initiates each of the independent electron bunches from the photocathode. Once the super radiator reaches adequate power for a given bunch, the drive laser is shifted in time to initiate the next selected bunch. This reduces the drive laser power requirements by a factor of 50 to only a few watts.

Figure 3: The SRF half-cell provides the initial energy gain for the electron beam. The returning beam is phased to deposit its energy into the SRF cavities, i.e. the system is an ERL. The depressed collector in the beam stop captures the remaining ~0.5 MeV of electron beam energy which is converted to high voltage to drive the IOTs.

An oscillator wiggler is used in this example for producing the light. An amplifier wiggler could have been used but it may produce a greater energy spread in the electron beam which would deteriorate the performance of the depressed collector. Results with the Jefferson Lab FEL’s oscillator wiggler demonstrate that the terahertz radiation in the system and the operation of the high power optical cavity mirrors\textsuperscript{13, 15, 16, 17} can both be managed to achieve the desired power levels.

### 2.3.3 Super Compact FEL Concept 2

The Concept 2 FEL shown in Figure 4 is somewhat more complex than Concept 1. The gun, injector, accelerator/linac and beam stop cryomodules/cryounits of the compact design are combined into a single cryomodule but the beam stop is separate though still internal to the cryomodule.

Figure 4: Concept 2: In this super compact FEL design, all of the SRF cavities are in a single cryomodule. The electron beam that has passed through the wiggler passes through the accelerator in the opposite direction as the initial electron beam. The IR oscillator wiggler provides the 1 kW of light to be amplified in the IR amplifier wiggler. The system could also operate with only an oscillator wiggler with a super radiator. The super radiator performs the same function as in Concept 1.

The SRF half-cell, see Figure 5, provides the initial energy gain for the electron beam and along with the next three cells functions as the injector. The three and one-half SRF gun-injector cells will provide 7.5 MeV of energy gain to the electron beam. The gun-injector cavities are best when operated near 10 MeV/m to optimize control of the beam...
emittance and to manage coupler power handling issues. For the accelerator cavities 15 MeV/m is selected as an optimum for minimizing the RF heating and minimizing the longitudinal beam emittance growth. The beam stop cavities operate at 7.6 MeV/m.

Following the IR amplifier wiggler, the electron beam has a full energy spread roughly four times the percentage of the beam power that is extracted from the electron beam, i.e. 6 percent or slightly less than 3 MeV for the example in this paper. The magnetic optics of the final corner magnet arc and the splitter magnet that redirects the beam back into the accelerator translate the energy spread into a longitudinal distribution in space in the direction of the beam. Consequently, these electron beam bunches see slightly different deacceleration RF electric fields. When these bunches reach the 7.5 MeV level, the energy spread will be below 0.5 MeV.

At the 7.5 MeV point for the deaccelerating electrons they encounter a magnet field, see Figure 3, and head towards the beam stop SRF cavities where ~6.5 MeV of energy is converted to RF to feed the gun-injector SRF cavities via the magic T couplers. The fields in the beam stop cavities will build to roughly 7.6 MeV/m. The remaining 0.5-1 MeV of beam energy is collected in the beam stop's depressed collector. A Direct Current (DC) converter reduces the voltage to the levels required to drive the gun-injector Inductive Output Tubes (IOTs).

There is roughly a 1 percent overall inefficiency in recovering the full 6.7 MW of electron beam power. This is the result of the differential RF deacceleration in the accelerator not exactly matching the post IR wiggler electron beam’s energy spread. To complete the energy balance, an additional 75 kW of RF power must be supplied to the gun-injector and accelerator SRF cavities beyond the 100 kW required to produce the directed energy.

While an oscillator wiggler would be fine for producing 100 kW of output light as is Concept 1, in Concept 2 an amplifier wiggler has been used. Initially the electron beam can be passed through an IR oscillator wiggler tuned to the 3\textsuperscript{rd} harmonic that has very high gain, and consequently for an FEL, low efficiency. The optical power in the IR oscillator wiggler’s optical cavity can be kept below 10 kW with an extracted power of 1 kW assuming a 10 percent outcoupling mirror has been used. This will make it easier to suppress the fundamental mode and reduce all of the other concerns by two orders of magnitude. Further, both the fundamental mode light and the harmonic light above the 3\textsuperscript{rd} harmonic can easily be removed from the 1 kW of extracted light. Note, the Jefferson Lab FEL’s oscillator wiggler has already operated at power levels over fourteen times this level.\textsuperscript{13}

Upon exiting the IR oscillator wiggler, the 0.3 mm long electron beam bunches are internally bunched at the period of the extracted light, 1.625 microns. The magnetic optics of the return arc are set to be isochronous and achromatic so that the internal bunching is preserved when the electron bunches enter the IR amplifier wiggler. This significantly enhances the amplification in the IR amplifier wiggler. The 1 kW of pure 3\textsuperscript{rd} harmonic light from the IR oscillator wiggler is fed into
the IR amplifier wiggler where the light is amplified 100 fold for the 100 kW light output. A mirror at the end of the IR amplifier wiggler beam line directs the light to the Beam Director mirror system for targeting.

3. CRYOGENIC HEAT LOADS

The weight of the Helium refrigerator required to operate SRF cavities is directly related to the cryogenic heat loads. To achieve an ATFEL these loads must be kept to a minimum. There are two ways to reduce the cryogenic heating: reduce the RF heating of the SRF cavities, and minimize the static heat loads from the mechanical connections between the SRF cavities and the exterior of the cryomodule that are at ambient temperature.

For the RF heating, increasing the $Q$ of the cavities has the largest effect. Reducing the RF frequency has a modest effect. However as stated earlier the smaller size and lower weight of the cryomodules push the frequency to the higher end of the broadly optimal region 400 MHz - 800 MHz and 750 MHz has been selected for this discussion.

Lowering the accelerating gradient reduces the RF heating linearly with gradient for a fixed total accelerator energy. However, the longitudinal emittance of the electron bunches increases roughly linearly with accelerator length, and this can have a significant effect on laser output. For this discussion gradients of 10 MeV/m have been selected for the gun-injector region and 15 MeV/m for the Accelerating section of the cryomodule.

3.1 Increasing SRF Cavity $Q$s

$Q$ can be increased by operating at lower temperatures and reducing residual resistance as can be seen in Figure 4.\textsuperscript{18}

![Figure 6: SRF cavity $Q$s increase significantly by reducing the residual resistance and lowering the operating temperature.\textsuperscript{18}](image)

An operating temperature of 1.6 K appears optimal since going even lower would begin to significantly increase the refrigeration size and power requirements due to the low Helium vapor pressures.\textsuperscript{19} Most existing large installations of SRF cavities such as the Jefferson Lab FEL and nuclear physics CEBAF accelerators operate near 2 K. On average their cavities have residual resistances in the 20-50 nOhm region where the effect of further lowering operating temperature is significantly less. For this ATFEL discussion, 1.6 K will be taken as the optimal operating temperature.

Recent fundamental SRF cavity R&D has resulted in two demonstrations of significant reductions in residual resistance. Figure 5 shows results from Jefferson Lab using single grain Niobium cavities and Figure 6 shows results from the DESY lab in Germany using electropolished fine grain cavities. The improvements come from a combination of better understanding the fundamental physics of the SRF properties of Niobium and fabrication process improvements.
Figure 7: Jefferson Lab Niobium single crystal cavity results showing very high $Q$s with minimal reduction for increasing accelerating field.\textsuperscript{18}

Figure 8: Fine grained electropolished cavities results at 1.3 GHz from DESY in Germany show both enhanced $Q$ and very low $Q$-drop with increasing accelerating gradient.\textsuperscript{20}
Scaling the Jefferson Lab and DESY results to an ATFEL operating at 750 MHz both single/large grain cavities and electropolished fine grain cavities should result in cavities with residual resistances below 3 nOhm. The resultant $Q_s$ should be better than $5 \times 10^{10}$ in the 10 - 15 MeV/m gradient region. The resultant RF heating will be approximately 2 W/m in the gun-injector and 5 W/m in the accelerator for these field strengths and $Q_s$.

Figure 7 shows a design of a 750 MHz cavity that will be capable of amp level currents that has been designed for the Navy. This design will more than meet the requirements of an ATFEL.

3.2 Static Heat Loads

Due to high RF heating, only modest efforts have historically been made on reducing static heat loads on the cryomodules. Engineering estimates indicate that the cryomodule linear heat loads can be reduced to 0.2 W/m, and cryomodule end cap heat loads can be reduced to 5 W per end cap. The heat from the higher order mode couplers is included in the linear heat load estimate. The significant reduction in heat from the higher order mode couplers compared with existing designs comes from introducing thermal heat gaps in the designs.

3.3 Total Cryogenic Heat Load

Assuming the $Q_s$ and gradients discussed in the prior section, the total ATFEL cryogenic heat loads are shown in Table 1:

<table>
<thead>
<tr>
<th>System</th>
<th>Energy (MeV)</th>
<th>Gradient (MeV/m)</th>
<th>Packing Factor</th>
<th>Length (m)</th>
<th>Static Heat (W)</th>
<th>1.6 K RF Heat (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun-Injector</td>
<td>7.5</td>
<td>10</td>
<td>0.5</td>
<td>2.4</td>
<td>5.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Accelerator</td>
<td>37.5</td>
<td>15</td>
<td>0.8</td>
<td>3.1</td>
<td>5.6</td>
<td>12.4</td>
</tr>
<tr>
<td>Beam Stop</td>
<td>[6.5 + 1.0]*</td>
<td>7.6</td>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>FEL Cryomodule</td>
<td>45</td>
<td></td>
<td></td>
<td>5.5</td>
<td>10.9</td>
<td>15.1</td>
</tr>
</tbody>
</table>

The resultant total Cryogenic Heat is 26 Watts.

* The beam stop cavities remove 6.5 MeV and the depressed collector removes 1.0 MeV of electron beam energy.
4. SUBSYSTEMS

Achieving an ATFEL requires tight integration of the multiple subsystems with each other and the C-130J-30 platform as will be seen in the following subsections.

4.1 Cryogenic System
Using largely off-the-shelf items, a weight estimate of 28,000 pounds has been made for a 100 W 1.6 K Helium refrigeration system for the 1 MW strategic airborne FEL.\textsuperscript{23} The weight estimate of 5,000 pounds has been made for the 26 W system needed for the ATFEL in this discussion based on a simple scaling of the refrigeration requirements and the assumption that much of the weight of the off-the-shelf items can be significantly reduced by using advanced materials. In that the off-the-shelf items have been designed to be supported by concrete floors where weight was not a concern, this assumption appears reasonable pending preengineering studies.

The weight is also kept low by having the roughly 40 kW of rotary power needed for the high pressure ambient temperature Helium compressors delivered via a direct drive from the jet engine in the APU. This slightly lowers the electric generator requirements thereby lowering its weight and removes the requirement of a heavy electric motor.

4.2 Magnet System
To eliminate the magnet electric power systems, cooling systems, etc., all of the magnets will be based on permanent magnets. A few of the magnets will have small trim coils that can effect the fields by a few percent. An estimate has been made of 13,000 pounds for the weights of the magnets based on scaling the magnet weights of similar systems for the 45 MeV system.\textsuperscript{24, 25}

4.3 RF System
The total RF requirement is 100 kW for the directed energy, plus 75 kW for the extra energy going into the electron beam so the returned electron beam will go cleanly into the beam stop’s depressed collector, plus 25 kW for RF control required to manage microphonics for a total RF power requirement of 200 kW. The RF power will be provided by several IOTs. Most efficient control is achieved when each cavity has its own RF source. With the efficiency of 750 MHz IOTs at 72 percent, the average electrical power for the RF system is just under 280 kW.

4.4 Electric Power System
The RF system at 280 kW dominates the overall electric power requirements. Requirements for the Helium refrigerator cold box, magnet trim magnets, drive laser for the gun, active damping system, directional mirror controls, cooling system controls, electron beam steering, etc. will require an additional 20 kW. A 300 kW power system driven by the APU will meet these requirements.

4.5 Cooling Systems
The cooling system will be sized to remove the 80 kW of waste heat in the IOTs, the 75 - 120 kW of heat deposited in the beam stop’s depressed collector plus the 40 kW of heat in the Helium refrigerators high pressure compressor for a total of 240 kW of cooling. The bleed air system on the C-130J-30 will be used via an air cycle machine to provide this cooling.\textsuperscript{26}

4.6 Vibration Damping System
A nice feature of an FEL is that there are relatively few components that require alignment with the directional mirror, and the electron beam can be steered in real-time as part of the alignment system. For mechanical vibrations, systems that have been developed for the Airborne Laser (ABL) program should more than meet all requirements.

4.7 Shielding System
A FEL when running produces very little radiation. If the beam is hitting anything except the final beam stop, the FEL will not be working. However, there can be some mostly gamma and x-ray radiation associated with field emission from the cavities and dark current electrons from the gun. In addition, if the electron beam were to hit something, there would be radiation for a fraction of a microsecond. Appropriate shielding will be provided by a very small amount of highly localized lead for the dark current electrons plus a 20 cm wall of the plane’s jet fuel placed in a tank between the FEL and
the crew. By arranging that this fuel tank is the last one used, the FEL would not be in operation when the tank is being used. Consequently, the shielding weight is very low as the fuel would already be present in any operational situation.27

4.8 Auxiliary Power Unit
The SRF cavities must be kept at liquid Helium temperatures at all times, i.e. below 4.5 K. An APU meets this requirement so that the Helium refrigerator can be run at least in a minimal heat load configuration at all times.

The total energy requirement for the APU when the FEL is in operation is 300 kW for the electrical systems, plus 40 kW for the Helium refrigerator high pressure compressor. The energy for the disposal of waste heat comes from the aircraft engine bleed air system.26 When the FEL is in a hibernate mode on the ground with the liquid Helium at 4.5 K, the total power requirement will be less than a few percent of the maximum requirement.

With MW level airborne APU’s currently under development28, 29 the 300 kW requirement can easily be met.

5. TOTAL SYSTEM WEIGHT

Table 2 provides estimates for the weight for the ATFEL subsystems. The weights for the heavier subsystems have been discussed above. The other weights are based on scaling weights from the airborne strategic 1 MW FEL.14

Table 2: ATFEL Subsystems and Weights

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Components</th>
<th>Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power generation &amp; air</td>
<td>Auxiliary Power Unit (except for generator)</td>
<td>500</td>
</tr>
<tr>
<td>Cooling</td>
<td>Heat removal, heat exchangers</td>
<td>500</td>
</tr>
<tr>
<td>AC generation</td>
<td>Electric generator, power conditioning</td>
<td>700</td>
</tr>
<tr>
<td>Electron beam gun</td>
<td>Laser</td>
<td>100</td>
</tr>
<tr>
<td>Cryostat</td>
<td>Gun, Injector, Accelerator</td>
<td>2,800</td>
</tr>
<tr>
<td>RF</td>
<td>IOTs, waveguides, feedback</td>
<td>300</td>
</tr>
<tr>
<td>Electron beam transport</td>
<td>Magnets, magnet chambers</td>
<td>13,000</td>
</tr>
<tr>
<td>Wigglers</td>
<td>Magnetic elements, mirrors</td>
<td>1,500</td>
</tr>
<tr>
<td>Vacuum</td>
<td>Piping &amp; pumps</td>
<td>500</td>
</tr>
<tr>
<td>Mechanical support</td>
<td>Magnets, vacuum system</td>
<td>2,000</td>
</tr>
<tr>
<td>Beam stop collector</td>
<td>Collector, shielding</td>
<td>500</td>
</tr>
<tr>
<td>1.6 K Helium</td>
<td>High pressure Helium compressors, expanders, heat exchangers, cold box</td>
<td>5,000</td>
</tr>
<tr>
<td>Directional mirror</td>
<td>Mirror, optical transport</td>
<td>2,000</td>
</tr>
<tr>
<td>Vibration damping</td>
<td>Active elements, supports</td>
<td>1,000</td>
</tr>
<tr>
<td>Shielding</td>
<td>FEL area, personnel areas</td>
<td>100</td>
</tr>
<tr>
<td>Contingency</td>
<td></td>
<td>4,500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>35,000</strong></td>
</tr>
</tbody>
</table>

The goal has been met for getting the weight more than 10,000 pounds below the maximum load capacity (46,812 pounds) of a C-130J-30. If the estimates prove accurate when the preengineering studies are performed and the substantial weight contingency is not required, than considerable capacity is available for other tactical systems.
6. ATFEL IN THE C-130J-30 CARGO BAY

An expanded view of an FEL in the cargo bay of a C-130J-30 is shown in Figure 8. The Concept 1 FEL at 12 meters long, 2.5 meters wide, and 1.5 meters high fits well within the cargo bay that is 16.9 meters long, 3.12 meters wide and 2.74 meters high. Adequate space exist outside the footprint of the FEL and within the loop of the electron beam for all of the peripheral equipment. In addition there is space towards the front of the platform for additional equipment and crew.

![Figure 10: SRF based Concept 1 FEL in the cargo bay of a C-130J-30](image)

The distribution of weight appears to be well balanced across the center of the aircraft. The FEL can also be rotated to point if the opposite direction if desired.

7. MEETING TACTICAL MISSION REQUIREMENTS

Only requiring jet fuel for the APU to operate, an ATFEL will perform in almost any environmental conditions. The directed energy beam can be on from milliseconds to hours and have any time structure and any intermediate power level desired. This allows the directed energy beam to function as a radar system that both acquires and images targets, i.e. the directed energy light can be steered and modulated for 4-D (3 space + time) tracking and targeting.14

The directed energy beam intensity can be varied by changing a combination of the intensity of the light from the super radiator going to the gun’s cathode, the position of the electron beam in the wigglers, and in Concept 2 the intensity of the 1 kW beam from the IR oscillator wiggler as it goes to the IR amplifier wiggler. With the RF at 750 MHz, the intensity variations can be performed as rapidly as every 1.33 nanoseconds allowing for very precise ranging. In addition, the intensity variations can be used to significantly enhance the signal to noise in imaging targets by only considering reflected light coming from the exact position of the target.

Because most lasers only operate for a few minutes or less at full power, the tactical usefulness of putting 100 kW of directed energy on a target for an extended period such an hour has not been explored in depth. An ATFEL would open up this tactical possibility thereby enhancing the military worth of airborne directed energy.3 The ability of the ATFEL to operate continuously for extended periods of time may also be useful in maintaining the standoff distance around the platform.

The time to go from standby to full operation is a critical parameter. An ATFEL will have several levels of standby on the way up to full power. On the ground the ATFEL can be put in a hibernate mode with the liquid Helium at 4.5 K and the APU or other local power source operating at a few tens of kW. It would then take about 20 minutes for the ATFEL to go from hibernate to 1.6 K standby with all systems ready. The ATFEL can be kept in a 1.6 K standby mode on the ground so that it would take less than a minute for all systems to be ready to operate at full power. It is likely that the ATFEL would be on essentially all of the time when the platform is airborne operating at low power as a radar system and ready to go to full power within milliseconds.
8. ATFEL TECHNICAL ROADMAP

The following steps will advance the concepts presented in this paper:

- Preliminary engineering is required for all of the ATFEL subsystems. The two subsystems that need to be worked first are the 1.6 K Helium refrigerator and the electron beam magnets. This will refine the weight estimates.
- The electron beam optics for the super compact FEL concepts need to be worked out to the same level of detail that the compact FEL design has been developed. In particular the electron beam optics and RF controls for the gun-injector, depressed collector beam stop and magic T RF couplers (Concept 2 only) require detailed design and prototyping.
- The details of the super radiator and IR amplifier/oscillator wigglers need development, especially with respect to how they interact with and effect the electron beam.
- The integration of the ATFEL into the C-130J-30 and other platforms of interest needs development including integration of the APU, vibration suppression, and the beam director mirror systems.

The Navy and JTO’s current work on developing a 100 mA injector, SRF cavities and cryomodules, compact FEL design, optical systems, and FEL operations at the 10+ kW level will meet most of the other requirements for consideration of an ATFEL over the next several years.

9. SUMMARY

Assuming that preliminary engineering and accelerator physics work confirm the weight estimates and the super compact FEL designs, the concepts presented in the paper demonstrate that an ATFEL could become a valuable tactical platform. The possibility of an ATFEL comes from using the 3rd harmonic generation of the directed energy light, the recent R&D results that significantly lower the RF heating in SRF cavities at 1.6 K, and the systems concepts appropriate for an airborne platform. It is also worth noting that these ATFEL concepts with their small size, low weight, and low electric power requirements may prove useful in expanding consideration of where FELs can be deployed such as forward ground systems, small ships, submarines, relay mirror systems, airships, and space based systems.

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