Design Analysis for a 100-MeV Inverse Čerenkov Laser Accelerator*

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Abstract
The analysis of a 100-MeV demonstration experiment based upon inverse Čerenkov acceleration (ICA) is presented. This experiment would use the Accelerator Test Facility (ATF) at Brookhaven National Laboratory. With 50-GW of delivered laser peak power from the ATF CO₂ laser, our analysis indicates the 65-MeV ATF e-beam can be accelerated to >165 MeV using three stages of acceleration in ~1 m of total length. The number of electrons accelerated can be raised to ~10⁹ by prebunching the e-beam using an already available device.

II. EXISTING ICA EXPERIMENT

An inverse Čerenkov laser acceleration experiment is currently being performed at the ATF [1]. Hydrogen gas (P = 1.7 atm) is used in a gas cell to slow the phase velocity of the laser light to match the electron velocity. The beams intersect at a Čerenkov angle of θ_c = 20 mrad with an interaction length of 20 cm.

The present gas cell design is already near optimum for the ATF conditions and can be used as the basis for a multistaged 100-MeV ICA demonstration experiment. Since one stage gives 38-MeV energy gain (assuming 50-GW delivered laser peak power), three stages will yield >100 MeV energy gain. The only major changes to the existing ICA experiment needed are upgrading the ATF CO₂ laser to produce 100-GW peak power and modifying the gas cell system to recycle the laser beam. This latter issue is discussed in more detail next.

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III. CONCEPTUAL DESIGN FOR 100-MeV DEMONSTRATION EXPERIMENT

Figure 1 is the simplified conceptual arrangement for the 100-MeV ICA demonstration experiment. A small portion of the drive laser power (~120 MW) is sent to a prebuncher; the rest of the power (~100 GW) is sent to the 3-stage accelerator.

Prebunching the e-beam before it enters the multistaged accelerator will significantly enhance the experiment. Without prebunching the electrons enter the multistaged accelerator at all phases resulting in only a small fraction of electrons being accelerated to the full 100-MeV energy gain. The existing gas cell being used in the current ICA experiments can be used as a prebuncher. Only ~120 MW of laser peak power is needed to drive the prebuncher and will give an optimum bunching distance \( z_b \approx 20 \) cm. At this point the prebunched e-beam will enter the multistaged accelerator.

A. 3-Stage ICA Accelerator Concepts

Two possible arrangements for the multistaged accelerator are shown in Figures 2 and 3. In the first concept (Figure 2), the incoming radially polarized laser beam reflects off a 45° mirror, which has a small hole in its center for passage of the e-beam. The laser beam then reflects off a curved axicon and is focused down onto the e-beam. (The purpose for using a curved axicon will be explained later in Section III.B.) After intersecting the e-beam in the first stage, the spent laser beam reflects off a slightly conical cylindrical mirror tube. This tube functions the same as the curved axicon and focuses the laser light back onto the e-beam in the second stage. The process repeats itself for the third stage.

This first concept is very similar in arrangement to the existing ATF ICA experiment [1], which uses a flat axicon rather than a curved one, has only one stage of acceleration, and does not use cylindrical mirror tubes.

One disadvantage of the first concept is the length of gas-filled space between the acceleration stages, which leads to additional scattering of the electrons by the gas molecules. Similar to the present ICA experiment, each interaction region is 20-cm long. This means the space between the stages must be >20 cm. Hence, for this first concept the total 3-stage accelerator length is ~110 cm.

Figure 3 depicts an alternative concept for the 3-stage accelerator that minimizes the distance between stages. The incoming radially polarized laser beam travels through a 45° mirror with a large hole in its center. The laser beam reflects off a waxicon, which converts the beam into a hollow one while maintaining its radial polarization characteristics. This hollow beam is directed off the 45° mirror to the curved axicon where it is focused onto the e-beam. The spent laser beam then immediately reflects off the slightly conical cylindrical mirror tube towards the second stage, and the process repeats itself for the third stage. Since the incoming laser beam...
does not need to travel through the mirror tubes as in Figure 2, the diameter of the tubes can be reduced thereby decreasing the space between acceleration stages. The total accelerator length of this second concept is ≈70 cm.

**B. β-Slippage Compensation**

In the preceding concepts, the curved axicon helps compensate for phase slippage between the electrons and light wave as the electrons gain energy within each interaction region. The Čerenkov angle \( \theta_c \), given by \( \cos \theta_c = (1/n\beta) \), where \( n \) is the index of refraction of the gas and \( \beta \) is the ratio of electron velocity to the velocity of light, changes as the electrons gain energy. By varying the Čerenkov angle within the interaction region it will be possible to maintain near optimum phase matching as the \( \beta \) of the electrons increases. This can be done by using a slightly concave axicon such that the angle of intersection is slightly larger (~1 mrad for the ATF conditions) at the end of the interaction region than at the beginning. The slightly conical shape of the cylindrical mirror tubes also accomplishes this same effect. An alternative method for β-slippage compensation is to use a slightly converging laser beam reflecting off a flat axicon and straight cylindrical mirror tubes.

**C. Recycling Laser Beam**

Another issue implied in the preceding concepts is being able to reintersect the laser pulse with the electron bunch in the second and third stages. Due to differences in the electron drift velocity relative to the effective group velocity of the laser pulse, the relative drift distance between the electrons and light pulse over a distance \( L \) is

\[
\Delta z_{\text{drift}} = \theta_c^2 L.
\]  

The laser pulse length in space is \( \Delta z_l = c\tau_l \), where \( \tau_l \) is the laser pulse width in time. Thus, the ratio of these two distances is

\[
\frac{\Delta z_{\text{drift}}}{\Delta z_l} = \frac{\theta_c^2 L}{c\tau_l}.
\]

Hence, if for example, \( \theta_c = 20 \text{ mrad}, \tau_l = 100 \text{ ps}, \) and \( L = 110 \text{ cm} \) (see Figure 2), then the amount of slippage is 1.5% of the laser pulse length. Therefore, recycling the laser pulse should not be an issue.

**IV. SUMMARY**

Table 1 summaries the estimated performance for the 100-MeV ICA demonstration experiment.

<table>
<thead>
<tr>
<th>ATF Parameter</th>
<th>Assumed Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector</td>
<td>65 MeV e-beam</td>
</tr>
<tr>
<td>CO₂ Laser Peak Power</td>
<td>50 GW (delivered)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ICA Parameter</th>
<th>Estimated Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Gain</td>
<td>95 to 125 MeV (net)</td>
</tr>
<tr>
<td># of Accelerated</td>
<td>&gt;5 × 10⁸</td>
</tr>
<tr>
<td>Electrons/Pulse</td>
<td>1st Concept: &gt;92 MeV/m</td>
</tr>
<tr>
<td>Energy Gradient</td>
<td>2nd Concept: &gt;143 MeV/m</td>
</tr>
</tbody>
</table>

The effect on e-beam emittance requires additional analysis to extract emittance information from the models. Emittance growth is less of an issue for high-γ e-beams; however, the ATF e-beam energy is relatively low which will impact the emittance growth of the accelerated e-beam.

**V. REFERENCES**
