An Investigation of Monoenergetic Electron Beams for High-Energy-Density and Inertial Confinement Fusion Diagnostics

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Summary

- Modern electron-beam-generation techniques provide a broad range of available energies and beam qualities.
- These beams have the potential for more-accurate radiography, monoenergetic and tunable x-ray generation, and possibly direct electron diffraction measurements.

Electron-Beam Sources

RF gun

Modern RF accelerators have been used for the successful electron acceleration of dynamic targets [2]:
- low-energy, low-energy spread beams are a great asset for electron diffraction
- the mean-free path (MFP) of elastic scatter provides strong limits on the targets and useful beam energies
- typical electron acceleration goes through no more than 4 MFP

Accelerators

- Electron diffraction utilizes the wave nature of electrons to investigate crystal structure
- Diffraction is induced when the Bragg condition is met [5]
- A 20 MeV electron, with a wavelength of 0.06 nm, will satisfy this condition

Comparison of MFP of electrons using Born approximation in various materials

- Reflecting electron diffraction provides one potential solution to the target thickness limit [2]:
- co-timing and target alignment will prove to be challenging
- Thin, uniform, self-targeted targets coupled to a spectrometer provide another solution
- co-timing and detector construction will provide challenges to this technique

Inverse-Compton Scattering X-Ray Sources

- Electron beams can interact with lasers to form monoenergetic x-ray beams via inverse Compton scattering [4]:
- The x-ray beam inherits the beam qualities of the parent beams
- If high-intensity lasers are used, a nonlinear scaling with x-ray yield and x-ray energy begins to occur following these equations [6]

X-ray Source using S-397 Electron Beam

- A 100-pc, g-pummed system coupled to MTF-OPAL would nearly be equal in brightness to standard foil x-ray backlighters, but would be more tunable
- The same system coupled to OMEGA EP would exceed the standard x-ray backlighter brightness by a factor of 100

Electron Radiography

- MeV-scale electrons can essentially penetrate ICF and HED targets [8]
- and act as a radiography source [2]
- LWFA-generated electron beams can also be made more resistive to magnetic fields than protons. The resistance of a given charged particle to deflection by a magnetic field is given by [2]:

Electron Radiography

- The x-ray beam could also be increased in bandwidth by adjusting the electron beam parameters

References


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• RF accelerators can be purchased from commercial vendors in turn-key packages
  – the large size and costs associated with RF accelerators limit laboratories that can reasonably host one
  – applications needing incredibly precise beams benefit greatly from the small energy spread and emittance
  – the broad tunability of RF accelerators allows for a wide variety of beams to be generated from a single machine \[2\]

RF: radio-frequency
Laser wakefield accelerator (LWFA) technology can often be implemented on existing lasers at ICF/HED research facilities:

- the high emittances and energy spreads limit the use of LWFA beams
- applications that need hundreds of MeV or greater benefit from the small size afforded by the large gradients
- the technology is rapidly maturing, with beam quality constantly increasing [3,4]

<table>
<thead>
<tr>
<th>Accelerator type</th>
<th>Acceleration mechanism</th>
<th>Accelerating gradient</th>
<th>Beam energy spread</th>
<th>Beam emittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF accelerator</td>
<td>Conductive resonant cavities powered by an external RF source</td>
<td>~20 MV/m</td>
<td>&lt;1%</td>
<td>Microradians</td>
</tr>
<tr>
<td>LWFA</td>
<td>Laser–plasma interactions</td>
<td>&gt;1 GV/m</td>
<td>&lt;10%</td>
<td>Milliradians</td>
</tr>
</tbody>
</table>

**ICF:** inertial confinement fusion  
**HED:** high energy density
Electron Diffraction

- Electron diffraction utilizes the wave nature of electrons to investigate crystal structure
- Diffraction is induced when the Bragg condition is met [5]

\[ 2d \sin \theta = n \lambda \]
• Modern RF electron accelerators have been used for the successful electron diffraction of dynamic targets [1,5]
  – low-emittance, low-energy spread beams are a must for electron diffraction

• The mean-free path (MFP) of elastic scatter provides strong limits on the targets and useful beam energies
  – typical electron diffraction goes through no more than 4 MFP

Comparison of MFP of electrons using born approximation in various materials
• Reflecting electron diffraction provides one potential solution to the target thickness limits [5]
  – co-timing and target alignment will prove to be challenging

• Thick, uniform, self-tamped targets coupled to a spectrometer provide another solution
  – co-timing and detector construction will provide challenges to this technique
Inverse-Compton Scattering X-Ray Sources

- Electron beams can interact with lasers to form monoenergetic x-ray beams via inverse Compton scattering [6].
- The x-ray beam inherits the beam qualities of the parent beams.
- If high-intensity lasers are used, a nonlinear scaling with x-ray yield and x-ray energy begins to occur following these equations [4]

\[
E_{x\text{-ray photon}} = \frac{4\gamma_e^2 E_{\text{laser-photon}} N_{\gamma}}{1 + (\gamma_e \theta)^2 + \frac{a_0^2}{2N_{\gamma X}}} \\
N_{x\text{rays}} = \frac{\sigma_c N_{\text{lesser}} N_e}{\pi w_0^2}
\]

- An inverse Compton source can be built using the same accelerator that would be used for electron diffraction experiments.
- This x-ray source would be bright, tunable, and monoenergetic.
- The x-ray beam could also be increased in bandwidth by adjusting the electron beam parameters.

### X-ray Source using 5-MeV Electron Beam

<table>
<thead>
<tr>
<th>Laser</th>
<th>X-ray (KeV)</th>
<th>Bandwidth (eV)</th>
<th>X-ray yield per pC of electron</th>
<th>(a_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTW OPAL</td>
<td>4.24</td>
<td>9.26</td>
<td>(6 \times 10^6)</td>
<td>3.47</td>
</tr>
<tr>
<td>EP 1000 J</td>
<td>1.041</td>
<td>0.22</td>
<td>(1 \times 10^9)</td>
<td>1.65</td>
</tr>
<tr>
<td>EP 350 J</td>
<td>4.502</td>
<td>0.22</td>
<td>(4 \times 10^8)</td>
<td>4.52</td>
</tr>
<tr>
<td>EP OPAL</td>
<td>61.823</td>
<td>1479</td>
<td>(1 \times 10^9)</td>
<td>43.95</td>
</tr>
</tbody>
</table>

- A 100-pC system coupled to MTW-OPAL would nearly be equal in brightness to standard foil x-ray backlighters, but would be more tunable.
- The same system coupled to OMEGA EP would exceed the standard x-ray backlighter brightness by a factor of 100.

\(a_0\): unitless laser strength parameter

MTW: multi-terawatt

OPAL: optical parametric amplifier line
Electron Radiography

- MeV-scale electrons can easily penetrate ICF and HED targets [7] and act as a radiography source [8]

- LWFA-generated electron beams can also be made more resistant to magnetic fields than protons. The resistance of a given charged particle to deflection by a magnetic field is given by [2,8]

\[
B \times r = \frac{p}{q},
\]

where \( B \) is the magnetic field, \( r \) is the deflection length, \( p \) is the particle momentum, and \( q \) is the particle charge

- \( ^{3}\text{He} \) proton radiography has a magnetic rigidity of \( \sim 0.6 \text{ T-m} \) [9]

- A 300-MeV electron beam has twice the magnetic rigidity of \( ^{3}\text{He} \) protons and is well within the range of a typical LWFA source

- The electron beam also has range in materials that is two orders of magnitude higher than \( ^{3}\text{He} \) protons, allowing for denser targets or targets shielded by holhraums

![Diagram of electron radiography setup](image)

300-MeV image-plate electron radiograph of a NIF pellet mid-compression

![Graph showing PSL vs. x (mm)](image)
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