Applications of Intense CSR from a cw Linac at Jefferson Lab

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12000 Jefferson Avenue
Newport News, Virginia 23606

UVSOR Workshop on Terahertz Coherent Synchrotron Radiation September 23-25, 2007
Source Characteristics

- 1 microJoule per pulse, 75 MHz, 180 fs FWHM
  10 MW peak, 100 Watt average power
- Achieved using superconducting linac with cw rf
Overview of the CSR THz Programs at Jefferson Lab

• Tissue interactions and safety limits.
• Imaging.
• Spectroscopy development – signal to noise etc..
  ⇒ magnetism, dynamics of quasiparticles, spin
  ⇒ localization effects

Future
• Electro-optical detection
• Quantum coherence and control.
• Coherent Half- and Few-Cycle Sources for Nonlinear and Non-Equilibrium Studies.
Jefferson Lab, Newport News, VA

Home of 2 accelerators: each with superconducting linacs, photo-cathode guns
JLab Free Electron Laser facility

135 pC per bunch = 1 µJ
Pulse FWHM 200fs – 2 ps
75 MHz

All sources are simultaneously produced for pump-probe studies

75 MHz – achievable using superconducting linac in energy recovery mode
Superconducting linac cavity

Gun
Jefferson Lab Facility Spectroscopic Range and Power

Energy (meV)

Wavenumbers (cm$^{-1}$)


JLab THz

JLab FEL

Table-top sub-ps lasers

Synchrotrons

Globar
Coherent Synchrotron Radiation Generation - theory

Jackson, Classical Electrodynamics, Wiley, NY 1975

Electric field for single particle:-

\[
\vec{E}_\omega = ec^{-1} \int_{-\infty}^{+\infty} \frac{\vec{n} \times [(\vec{n} - \vec{\beta}_e) \times \vec{\beta}_e] + cR^{-1} \gamma^{-2} (\vec{n} - \vec{\beta}_e)}{(1 - \vec{n} \vec{\beta}_e)^2 R} \exp[i \omega (\tau + R / c)] d\tau
\]

REFERENCES


Coherent Synchrotron Radiation Generation - theory

\[
\frac{d^2I}{d\omega \, d\Omega} = \left[ N[1 - f(\omega)] + N^2 f(\omega) \right] \times \text{[single particle intensity]}
\]

\( f(\omega) \) is the form factor – the Fourier transform of the normalized longitudinal particle distribution within the bunch, \( S(z) \)

\[
f(\omega) = \left| \int_{-\infty}^{\infty} e^{i \omega \hat{n} \cdot \hat{z}/c} S(z) \, dz \right|^2
\]

Larry Carr

\[
\frac{dE}{d\Omega} \approx 2 \times 10^{-25} \text{ J/cm}^4/\text{electron}
\]

REFERENCES


JLab THz Beam Schematic with Optical Beam Ray-tracing

M1

F3

M4

200x200mm

60x60mm

F2

M2

200x200mm

60x60mm

M1

200x200mm
JLab THz Beam Pattern on Mirror 1

0.1 THz
3.3 cm⁻¹

1 THz
33 cm⁻¹

10 THz
330 cm⁻¹
Jefferson Lab THz spectra and total power

![Graph showing THz spectra and total power with various power levels and time intervals.]

- 100 MHz 100 pC
- 150 x 150 mr
- 0.1 ps
- 0.3 ps
- 1.0 ps

Power levels: 54 W, 540 W, 840 W
JLab Terahertz Beam Extraction and Transport

diamond window

M1

M2

M3

Shutter/viewer & camera

V1

M1
Mirror 1 - courtesy of Richard Wylde, (Thomas Keating)
JLab power permits large area imaging ~ m²

Optical transport output in User Lab

Real time image

Ray trace

10mm²
Challenges of Stand-off THz Imaging

- Providing sufficient THz power to illuminate a large field of view and to image in real time
- Properly collecting the scattered THz radiation from the target region (transmission mode generally not useful)
- Filtering of the THz induced thermal IR
- Properly imaging onto a detector array
- Creating imaging arrays designed specifically for THz imaging
Imaging / bio-medical cancer screening

Basal cell carcinoma shows malignancy in red.  Teraview Ltd.

1 mW source images 1 cm$^2$ in 1 minute

100 W source images whole body (50 x 200cm) in few seconds
Imaging / security screening at portals


Spectra of explosives courtesy of Teraview
Jefferson Lab & U. of Delaware Team
THz Imaging Schematic

2 Watts of broadband light onto 75mm x 75mm field. ~10^4 camera elements, so 200 microWatts per pixel. Scattering ~ 0.1%, so 0.2 microWatts per pixel. Noise level, 1 nanoWatt, so S/N is ~200.
The Camera

Micron™ OEM Core

High performance thermal imaging from the world’s smallest infrared camera

Micron OEM Camera Core—A Success Story
Over 12,000 Microns have been delivered in support of applications requiring the smallest, lightest, and lowest power thermal camera. Over 90% of all Micron cameras have been integrated into sy

Really Uncool
Eliminating the traditional thermoelectric cooler (TEC) reduces overall camera weight, as well as enabling ultra-low power operation and a turn-on time of less than 2 seconds.

THz Induced Thermal IR

- Images taken using the stock Ge lens
- THz passes through paper target and is reflected off of the imaging target
- Heating due to absorption of THz heats the paper and the imaging target, producing the thermal IR seen above
Test of Imaging Resolution

- Raw THz images are processed to reduce the background and improve contrast
- Current configuration resolved down to the 1mm wide contact pads
- Polyethylene lens filtered the thermal IR, but does not image well
THz Imaging Covered Target

CD mailer covering

cloth covering
4. THz effects

Duke U. - tune to intramolecular bonds to eliminate collateral damage

THEORETICAL AND EXPERIMENTAL BIOEFFECTS RESEARCH FOR HIGH-POWER TERAHERTZ ELECTROMAGNETIC ENERGY

23 Jan 07  Jill McQuade, PhD
Research Physiologist
Human Effectiveness Directorate
Air Force Research Laboratory
Many applications for THz sources
High-power sources and detectors are being developed
Bioeffects need to be understood for the health and safety of personnel
Bioeffects efforts need to catch up to or even lead technology development
Bioeffects data pertaining to the health effects of high-powered THz exposure are non-existent
<table>
<thead>
<tr>
<th>Name</th>
<th>Division</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Jill McQuade</td>
<td>HEDR</td>
<td>Physiologist: Project Lead</td>
</tr>
<tr>
<td>Dr. Bob Thomas</td>
<td>HEDO</td>
<td>Physicist: Modeling</td>
</tr>
<tr>
<td>Mr. Jason Payne</td>
<td>HEDR</td>
<td>Biomedical Scientist: Modeling</td>
</tr>
<tr>
<td>Ms. Nichole Jindra</td>
<td>HEDO</td>
<td>Biologist: Expt, pilot lead</td>
</tr>
<tr>
<td>Dr. Semih Kumru</td>
<td>HEDO</td>
<td>Physicist: Expt</td>
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<tr>
<td>Mr. Victor Villavicencio</td>
<td>HEDO-NG Cont</td>
<td>Physicist: Expt</td>
</tr>
<tr>
<td>Dr. Ron Seaman</td>
<td>HEDR–GD-AIES Cont</td>
<td>Physiologist: Expt, protocol</td>
</tr>
<tr>
<td>Mr. Alex Salazar</td>
<td>HEDR–GD-AIES Cont</td>
<td>Physiologist: Expt</td>
</tr>
<tr>
<td>Dr. Walter Hubert</td>
<td>HEDR</td>
<td>Molecular Biologist: Biotechnology</td>
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Brooks Terahertz Experiments & Modeling

- Performed at Jefferson Laboratory
- Experimental Validation of models
  - characterization of the beam
  - exposures of wet chamois, 2 phantoms

- $ED_{50}$ (2 s exposure) chamois = 7.14 W/cm$^2$
- Model predicted 4-5 W/cm$^2$
Laboratory layout for spectroscopy & pump-probe
Measured JLab – FEL THz Spectrum in Air

JLab - FEL THz spectrum

\( \tau_p \sim 350 \text{ fs} \)
Early IRSR experiments

Experimentation Issues – NSLS Signal to Noise

dynamic range 1000 in 1 sec.

with Larry Carr
Experimentation Issues – FEL Signal to Noise

FEL THz Source (40 kHz modulation)

dynamic range 50 in 1 sec.
Shear Interferometer – Sievers and Agladze, Cornell

linear array

path difference
Coherent synchrotron radiation measurements

Interferograms

Calculated spectra
Some of the JLab Team

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.
Jefferson Lab Facility Spectroscopic Range and Power

Energy (meV)

Flux (Watts/cm²)

Wavenumbers (cm⁻¹)

JLab THz

JLab FEL

Table-top sub-ps lasers

Synchrotrons

Globar


Conclusions

- We have a high power CSR THz source capable of illuminating a large field of view which can be imaged at full video rates
- Initial results have resolved features down to 1mm
- Filtering of the thermal IR is necessary to utilize the important properties of THz radiation
- Development of compact high power THz source will enable deployed systems (Advanced Energy Systems)
- We have a user program in place to look at biological effects
- We have just started our spectroscopy programs
Some of the JLab Team

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.

Photo taken Jan 16, 2007
EXTRA SLIDES
Example of niche of 4th. Generation $\rightarrow$ Si:H

**Defect Dynamics**

- $H^{(+)}_{BC}$
- $H_2^*$
- $IH_2$
- $V_2H$
- $VH_2$
- $VH_4$

**Luepke et al. CWM/Vanderbilt**

\[ T_1 = 7.8 \pm 0.2 \text{ ps} \]

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**References**

- Wm. & Mary Phys. Rev. Letts 88, 135501, 2002
- Phys. Rev. B63 195203 2001
- J. Appl. Phys. 93 2316, 2003
Experimentation Issues

Source Chop (ω) Detector

- NSLS Beam on, modulation on
- NSLS Beam on, modulation off
- NSLS Beam off, mod. off
- JLab Beam off, mod. off
- JLab Beam on, modulation off
- JLab Beam on, modulation on

NSLS Beamline U12IR
1.8K Bolometer Bruker 125
12mm aperture, no sample
600 mA beam current

Frequency (Hz)

dB(u)
Over the past 10 years Jefferson Lab has constructed and commissioned a next generation light source based on an Energy Recovered Linac.

Our experience with generating ultrafast electron beams and diagnostics, can help implementation of Cornell ERL.

This ERL, or an x-ray ERL yielding THz light could have a huge impact on high pressure research.
Summary

• Tremendous opportunities
• In class of our own
• Must stay at scientific frontiers
• Great local university teams
• Helping Florida State, Cornell, Daresbury and other 4th. generation light source facilities

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.
Daresbury data holds world record!!

Synchrotron SnCl$_4$/silica Daresbury 1998 200 secs


Paul Dumas and collaborators - many papers

Comparing Conventional THz Sources and Coherent THz Synchrotron

Larmor's Formula: \( \text{Power} = \frac{2e^2a^2}{3c^3}\gamma^4 \) (cgs units)

\( E = \frac{100V}{10^{-4}m} = 10^6 \frac{V}{m} \)

\[ a = \frac{F}{m} = \frac{10^6 V}{.5 \text{MeV} / c^2} = \frac{10^6 (3 \times 10^8)^2}{0.5 \times 10^6} \approx 10^{17} \frac{m}{\text{sec}^2} \]

\( \gamma = 200 \) and \( 200^4 = 10^9 !!!! \)

\( a = \text{acceleration} \)
\( c = \text{vel. of light} \)
\( \gamma = \text{mass/rest mass} \)
Synchrotron Radiation Generation - 2 time-scales

Statistics of an electron bunch in a storage ring

Coherent Synchrotron Radiation Generation

\[ \Delta t = \frac{1}{\gamma^2 c \gamma} = \frac{5}{4000^3 \times 3 \times 10^8} \approx 0.25 \text{ Attoseconds} \]

Electron(s)

Electric field

Intensity $|E^2|$

frequency (1/time)

Super-radiant enhancement

Thomas Jefferson National Accelerator Facility
Multiparticle coherence – Free Electron Laser

Spectrum of uric acid

$\text{cm}^{-1}$ spectral resolution Recorded at SFTC Daresbury
Schematic of JLab 4th. Gen. Light Source Operation

Niobium SRF Cavity with Oscillating Electromagnetic Field

Electron Beam

Cryomodule

Injector

Drive Laser

Gun

Total Reflector

Light Output

Output Mirror

Wiggler

Periodic Magnetic Field

Electron Beam

Laser Wavelength ~ Wiggler wavelength/(2\text{Energy})^2
Experimentation Issues

NSLS Beam on, modulation on
NSLS Beam on, modulation off
NSLS Beam off, mod. off
JLab Beam off, mod. off
JLab Beam on, modulation off
JLab Beam on, modulation on

Source  Chop (ω)  Detector

NSLS Beamline U12IR
1.8K Bolometer Bruker 125
12mm aperture, no sample
600 mA beam current
Electron Beam Energy = 3 GeV
Bending Radius = 5m
1 nc @ 100 MHz (100 mA)

4GLS 1x1nm
(x10^10 for multiparticle)

3GLS 10 x 500 microns
(x500 for ID)

2GLS 500x1000 microns

Gwyn Williams - file brt_1.bas
May 25, 2006
1st. Generation – parasitic use of nuclear and high energy physics machines

2nd. Generation – dedicated storage rings – higher current, lower emittance

3rd. Generation – storage rings with insertion devices (wigglers), lower emittance

4th. Generation – typically linac based, lower emittance, multiparticle coherence
Generic Light Source Landscape – Average Brightness

Electron Beam Energy = 3 GeV
Bending Radius = 5m
1 nc @ 100 MHz (100 mA)

LARMOR LIMIT

4GLS 1x1nm
(x10^10 for multiparticle)

JLAB FEL

JLAB THZ

FSU

LCLS XFEL

2GLS 500x1000 microns

4GLS 3x100 microns

Photon Energy (eV)

Photons/sec/0.1%BW/mm^2/milliradian^2

Gwyn Williams - file brt_1.bas
May 25, 2006
Generic Light Source Landscape – Peak Brightness

Electron Beam Energy = 3 GeV
Bending Radius = 5m
1 nc @ 100 MHz (100 mA)

MULTIPARTICLE ENHANCEMENT
4GLS 1x1nm 50fs FWHM
(x10^10 for multiparticle)

INSERTION DEVICE
3GLS 10 x 500 microns
(x500 for ID) 50ps FWHM

DIPOLE
2GLS 500x1000 microns
500 ps FWHM
Generic Light Source Landscape – Peak Brightness

- Electron Beam Energy = 3 GeV
- Bending Radius = 5m
- 1 nc @ 100 MHz (100 mA)

- JLAB THz
- FSU
- JLAB 4GLS UVFEL FLASH XFEL LCLS

- LARMOR LIMIT
- INSERTION DEVICE
  - 3GLS 10 x 500 microns (x500 for ID) 50ps FWHM
  - 2GLS 500x1000 microns 500 ps FWHM

- Multiparticle Enhancement

Photon Energy (eV)

Photons/sec/0.1%BW/mm²/milliradian²

Gwyn Williams - file brt_1.bas
May 25, 2006

Thomas Jefferson National Accelerator Facility

Jefferson Lab
First CSR Science: Josephson Plasma Resonance in Bi$_2$Sr$_2$CaCu$_2$O$_8$

Data from Nov. 2002

GHz

Reflectivity

Two fluid model

λ$_c$ = 21 µm

Frequency (cm$^{-1}$)

+ Indications for inhomogeneous superfluid
Non-linear dynamical effects using high field THz light


High electric fields are predicted to generate localized modes!

JLab collaboration with Al Sievers, Cornell U.