Nonlinear Compton Scattering

K.T. McDonald and D.P. Russell
Princeton University

Presentation at DOE Headquarters, Germantown
(October 12, 1990)
I.
The Nonlinear Compton Scattering Experiment
Particles & Fields

1800's

Experiment $\Rightarrow$ Fields exist 
(Ampère, Faraday, Hertz...)

Theory $\Rightarrow$ Elementary particles should exist 
(Maxwell, Boltzmann...)

1900's

Experiment $\Rightarrow$ Elementary particles exist 
(Thomson, Rutherford...)

Theory $\Rightarrow$ New fields should exist 
(Gluon, Higgs...)

Particle properties are greatly affected by a strong background field 
(More familiar in condensed matter physics)

Hawking: QED affected by strong gravitational field

Interest: QED in strong E-M waves.
Laser Acceleration of Particles
(Malibu, California, 1985)

Fundamental Physics During
Violent Accelerations

KIRK T. MCDONALD
Joseph Henry Laboratories
Princeton University
Princeton, New Jersey 08544

ABSTRACT

When a powerful laser beam is focussed on a free electron the acceleration of the latter is so violent that the interaction is non-linear. We review the prospects for experimental studies of non-linear electrodynamics of a single electron, with emphasis on the most accessible effect, non-linear Thomson scattering. We also speculate on the possibility of laboratory studies of a novel effect related to the Hawking radiation of a black hole.
**Nonlinear Effects**

A. Multiphoton Ionization of Atoms

- Voltage across Bohr radius $\sim 1.2 \text{ eV}$

$$E_{\text{LASER}} \sim 10^8 \text{ volts/cm}$$

$$I_{\text{LASER}} = \frac{E^2}{327} \sim 10^{13} \text{ watts/cm}^2$$

B. Multiphoton Interactions of Free Electron

- Voltage across laser wavelength $\sim 1 \text{ MeV}$

$$eE_2 \sim m c^2 \Rightarrow E \sim 3 \times 10^9 \text{ V/cm} \text{ for } \lambda \sim 10^{-4} \mu \text{m}$$

$$I \sim 10^{16} \text{ watts/cm}^2$$

C. Pair Creation; Light-by-Light Scattering

- Voltage across Compton wavelength $\sim 1 \text{ MeV}$

$$eE \frac{\lambda}{mc} \sim mc^2$$

$$E \sim 10^{16} \text{ volts/cm}$$

- But, only need this in pair rest frame!

- At SLAC, $q \sim 10^{-5}$, so $E_{\text{LAB}} \sim \frac{E}{10^5} \sim 10^{11} \text{ V/cm}$

$$I \sim 10^{19} \text{ watts/cm}^2$$
FUNDAMENTAL NONLINEAR FORCES

ELECTROMAGNETIC \rightarrow LINER \leftrightarrow SUPERSPOSITION OF FIELDS

STRONG WEAK \leftarrow NONLINEAR \rightarrow SELF-COUPLING OF GAUGE BOSONS

\begin{align*}
\text{but, vacuum polarization } & \Rightarrow \text{ nonlinearity in QED} \\
\text{light-by-light scattering} & \ (1935)
\end{align*}

No direct evidence for any fundamental nonlinear interaction!

\begin{align*}
\text{LEP II: solution to study} & \Rightarrow 20\ \text{GeV}
\end{align*}
LIGHT-BY-LIGHT SCATTERING EXPERIMENTS

LASER 1

50 GeV e

GeV PHOTONS

LIGHT-BY-LIGHT SCATTERING

LASER 2

MAGNET

SILICON-STRIP DETECTORS

\( e^+ e^- \) FROM
\( \gamma \gamma \rightarrow e^+ e^- \)

\( e^+ e^- \) FROM
\( \gamma \gamma \rightarrow e^+ e^- \)
PROPOSAL FOR AN EXPERIMENTAL STUDY OF
NONLINEAR COMPTON SCATTERING

R.C. FERNOW and H.G. KIRK
Brookhaven National Laboratory

L.J. BIGIO and N.A. KURNIT
Los Alamos National Laboratory

K.D. BONIN, K.T. MCDONALD,† and D.P. RUSSELL
Princeton University

\[ n \gamma_{\text{LASER}} + e \rightarrow \gamma' + e' \]

Submitted to Brookhaven National Laboratory

† Spokesperson
**FREE ELECTRONS IN A PLANE WAVE**

1. **Transverse Velocity**, \( v_\perp \)

\[
F = ma \implies eE = mc_0 v_\perp \implies \frac{v_\perp}{c} = \frac{eE}{mc_0^2} \equiv \eta
\]

so \( v_\perp \to c \) as \( \eta \to 1 \)

**Note:** \( \eta = \frac{1}{2\pi} \frac{eE^2}{mc_0^2} = \frac{1}{2\pi} \cdot \frac{\text{Voltage Drop per Wavelength}}{\text{Electron Rest Energy}} \)

2. **Effective Mass**, \( \tilde{m} \)

Due to the \( v_\perp \), the electron has mass

\[
\delta m = \frac{m}{\sqrt{1 - \frac{v_\perp^2}{c^2}}}
\]

Then really \( F = \delta ma \) so \( \frac{v_\perp}{c} = \frac{\eta}{\delta} \)

\[
\Rightarrow \delta = \sqrt{1 + \eta^2}, \quad \frac{v_\perp}{c} = \frac{\eta}{\sqrt{1 + \eta^2}}
\]

We say \( \tilde{m} \equiv \delta m = m \sqrt{1 + \eta^2} \) = **effective mass of the electron in the wave**
HIGHER HARMONIC RADIATION

When $v \to c$, higher multipole radiation becomes important

$$\frac{dV_n}{dt} \sim \left(\frac{v}{c}\right)^{2n-2}, \quad \text{Dipole radiation}$$

The cross section for scattering to final photon of frequency $\nu_f$ is

$$\sigma_n \sim \nu_0^2 (\nu^2)^{n-1} \quad (\eta \ll 1)$$

Compare with 'naive' QED analysis

$$\sigma \sim \frac{\alpha^{n+1}}{\mu^2} \sim \frac{\alpha}{\mu^2}$$

For $\eta \gg 1$ we have a kind of synchrotron radiation

$\Rightarrow$ Max. intensity at harmonic

$$\nu_n \sim \nu^3 \sim \eta^3 \nu$$

Close analogy to wiggler radiation (scattering of virtual photons of the magnet)

- Higher harmonics when $\eta = \frac{eB}{m_c^2} \frac{\lambda_0}{2\pi} \geq 1$
Nonlinear Compton Scattering Experiment

$10^5 e$

40 MeV

2 ps

1 mm spot

CCD array

Bragg Spectrometer

$E_{\gamma} \approx 3 KeV$

Pb slit

Ge(Li) detector

1 meter

Laser beam

$\lambda = 10 \mu m$

100 m joule

2 ps FWHM

Laser monitor

Deflection magnet

Graphite mosaic crystal

f3 mirrors

e beam

Beam 2
Must distinguish 1 6-keV x-ray from 2 3-keV x-rays, arriving within 2 picoseconds!

Figure 6. The scattering of monoenergetic x-rays by a graphite mosaic crystal. The scattering angle is always twice the Bragg angle $\theta_B$. The mosaic spread, $\Delta$, of orientations of the microcrystals results in a focusing geometry with angular acceptance $\Delta$.

Figure 7. X-rays of energy $E + \delta E$ are focused by Bragg reflection off a graphite mosaic crystal to a different point than those of energy $E$.

Data collection ~1 week (once debugged)
NONLINEAR COMPTON SCATTERING

TOTAL SCATTERING PROBABILITY = 0.25 PER ELECTRON

\[ E_e = 40 \text{ MeV} \]
\[ \lambda = 10 \mu \text{m} \]
\[ \eta_{\text{MAX}} = 0.4 \left\{ \text{2 ps limit} \right\} \]
\[ f/d = 3 \text{ MIRROR TO FOCUS} \]

\[ \eta = \frac{eE}{mc^2} \]

X-RAY PRODUCTION = BASIC TEST OF
SYNCHRONIZATION OF LASER AND LINAC.
PROPOSAL FOR AN EXPERIMENTAL STUDY OF NONLINEAR COMPTON SCATTERING

R.C. FERNOW, H.G. KIRK, and J. ROGERS
Brookhaven National Laboratory

I.J. BIGIO, N.A. KURNIT, and T. SHIMADA
Los Alamos National Laboratory

K.T. McDonald,† D.P. Russell, and M.E. WALL
Princeton University

Submitted to the Center for Accelerator Physics, Brookhaven National Laboratory

† Spokesperson
COEXISTENCE OF
THE LASER-GRATING
EXPERIMENT &
THE NONLINEAR
COMPTON EXPERIMENT
(NEED 8" ADJUSTMENT
OF CO2 PATH LENGTH
BETWEEN EXPERIMENTS)

SIDE VIEW

FOCUS

FOCUS

LASER LINAC

DIRECTED

COMPTON

BEAM

CRYSTAL

TOP VIEW

CO2 & DETECTOR

447.7
I. X-RAYS THAT COULD REACH THE GE DETECTOR AFTER SCATTERING OFF THE BRASS CRYSTAL

A. SCATTERING OF THE E-BEAM OFF RESIDUAL GAS
\(10^{-7} \text{ s} \times 10^{-5} \text{ Torr} \rightarrow 250 \text{ keV}\)
but only \(\frac{1}{4} \text{ keV}\) in 10\% bin at 4 keV

B. SYNCHROTRON RADIATION OF E-BEAM IN DUMP MAGNET
20° bend 150-MeV e/s \(\rightarrow \) \(\omega_0 \sim 0.6 \text{ eV}\)
\(N \sim 0.2/\text{electron}\)
\(\Rightarrow\) NO TAIL INTO 1 keV REGION

II. X-RAYS THAT COULD REACH THE GE DETECTOR WITHOUT SCATTERING OFF THE BRASS CRYSTAL

A. X-RAYS FROM THE BEAM DUMP ∼ 3 FEET BELOW THE GE DETECTOR

B. X-RAYS FROM THE COLLIMATORS IN THE UPSTREAM E-BEAM LINE

\(\Rightarrow\) MUST SHIELD GE DETECTOR WITH LEAD IF WANT TO DETECT \(\sim 1\) NONLINEAR COMPTON X-RAY PER \(10^{-7} \text{ e/s}\).
DATA COLLECTION

Goal: 1% bins in X-ray energy
- Scan upper 30% of energy spectra of first 4 harmonics
- 2% statistical accuracy per bin

Rate at 3rd harmonic:
- \(10^{-7}\) scatters per electron into 1% bin
  \(\Rightarrow\) Run with \(10^7\) electrons/pulse
  \(\Rightarrow\) 150 hours to scan 4 harmonics

Calibration 5 (of acceptance via ordinary Compton scattering)
- \(\sim 50\) hours

Total \(\sim 200\) hours

* CO2 laser performance is critical to observe nonlinear effects
  Goal: 50 mJ/pulse
  6 ps FWHM
  Focusable in f/2 mirror
  1 Hz operation
Department of Physics

6 December 1989

Dr. Kirk T. McDonald
Princeton University
Jadwin Hall
P.O. Box 708
Princeton, NJ 08544

Dear Kirk:

Thank you for your clear presentation of the proposal *The Nonlinear Compton Scattering Experiment* which has been given the experiment number “4”. The committee recommended approval of this experiment. Congratulations!

The committee did feel that there may be a severe background from beam halo colliding with walls. It was felt however that the best way to find out was to try. Thought should, never-the-less, be given to the problem.

Yours sincerely

Robert B. Palmer

RBP:kt

cc: CAP Steering Committee:
   E. Courant
   H. Focke
   S. Krinsky
   V. Radka
   A. Sessler
   P. Thieberger
   M. Blume
   H. Kirk
   N. Samios
   D. Sutter, DOE
II.

Princeton Involvement with the BNL Accelerator Test Facility
**Particle Accelerators**

Maxwell: Plane waves have $E \perp k$
so can't give net acceleration to a charge

Need $E \parallel k \Rightarrow$ wall or medium

But, wall destroyed in 1 cycle if

$$E \geq \frac{1 \text{ ion, pot.}}{\text{size of atom}} \approx \frac{10 \text{ volts}}{1 \AA} \approx 10^9 \text{ volts/cm}$$

Materials limit: $E_{\text{wall}} \leq 10^7 \text{ volts/cm}$

so $E_{\parallel} \sim E_{\text{wall}} \approx 1 \text{ GeV/meter}$

(Limit in a plasma may be somewhat higher!)

Stanford Linear Collider: 15 MeV/meter

'Tabletop' CO$_2$ Laser: $\sim 100 \text{ GeV/meter}$

'Tabletop' Nd:Glass (quadrupled): $\sim 1 \text{ TeV/meter}$

⇒ Laser-Grating Accelerator

  Inverse FEL
  Inverse Čerenkov

Plasma Beat Wave

...
Design of the Laser-Driven RF Electron Gun for the BNL Accelerator Test Facility

KIRK T. McDONALD

Fig. 1. Block diagram of the Brookhaven Accelerator Test Facility.

Fig. 2. Section through the RF gun. Except for the waveguide feed, the gun is axially symmetric. The $1\frac{1}{2}$-cells of the gun are 8 cm long.

Fig. 8. The transverse emittance (solid curves) as a function of the peak RF field on the cathode, and the optimum phase (dashed curve) for the laser pulse to strike the cathode. Other parameters are as in Table 1.
Methods of Emittance Measurement

K.T. McDonald and D.P. Russell

Frontiers of Particle Beams; Observation, Diagnosis and Correction

Proceedings of a Topical Course
Held by the Joint US-CERN School on Particle Accelerators at Anacapri, Isola di Capri, Italy, October 20–26, 1988

M. Month S. Turner (Eds.)

Fig. 1. ATF Beamline.

Fig. 2 A Phosphor-Screen Beam-Profile Monitor.

Fig. 3. Pepper-Pot Technique

Fig. 4. A TM$_{130}$ rf cavity used to impart a time-dependent transverse deflection to a particle beam.
A BEAM-PROFILE MONITOR FOR THE BNL ACCELERATOR TEST FACILITY (ATF)

D. P. Russell and K. T. McDonald
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

Proceedings of the 1989 IEEE Particle Accelerator Conference

Accelerator Science and Technology

March 20–23, 1989
Chicago, IL

Proceedings Editors
Floyd Bennett
and
Joyce Koepa
Argonne National Laboratory

Fig 1. The ATF beam-profile monitor
X-RAY DIAGNOSTIC OF ELECTRON - CO₂ LASER INTERACTIONS

VERIFIED: PICOSECOND SYNCHRONIZATION OF Beam WITH LASER.
Preliminary Tests and Modeling of the 10.6 μm Picosecond Pulse-Formation System Experiment

CAP-ATF-Tech. Note #7

I. Pogorelsky
Brookhaven National Laboratory and Spectra Technology, Inc.

P. Russell
Princeton University

---

(a) Nd:YAG (1.06 μm) s-polarized control beam
CO₂ (10.6 μm) p-polarized beam
Transmitted 10.6 μm radiation

(b) Time-delayed control pulse (s-polarized)
Transient 10.6 μm pulse (p-polarized)

---

ONE-_STAGE REFLECTION SWITCHING

TRANSMISSION SWITCHING
ATF Experimental Beamline

Focus  Dipole

Laser Linac  Compton  Bragg Crystal

Ge Detector

47.7

8 35 8 26.4

10

63.1

10 10

40

BPM

Faraday Cup

Built by Princeton
3-GHz Faraday Cup

To 50-Ω Transmission Line

PIN DIAMETER 102
PIN HEIGHT 9/16

2 7/16 1 1/16 0 5/8

2 1/4 2 000 0 870 0 5/8
Simultaneous x- and y-Focusing with a Single Bend Magnet

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ [deg]</td>
<td>20.5</td>
<td>30.0</td>
</tr>
<tr>
<td>$\rho$ [cm]</td>
<td>13.9</td>
<td>16.7</td>
</tr>
<tr>
<td>$B$ [kgauss]</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>$l_1$ [cm]</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>$l_2$ [cm]</td>
<td>216</td>
<td>88.5</td>
</tr>
<tr>
<td>$\beta_1$ [deg]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\beta_2$ [deg]</td>
<td>8.24</td>
<td>9.5</td>
</tr>
<tr>
<td>$\delta R_{12}/\delta \beta_2$ [mm/mrad/deg]</td>
<td>0.265</td>
<td>0.0945</td>
</tr>
<tr>
<td>$\delta R_{44}/\delta \beta_2$ [deg$^{-1}$]</td>
<td>-0.123</td>
<td>-0.107</td>
</tr>
</tbody>
</table>
The Brookhaven Accelerator Test Facility

D.P. Russell, K. Batchelor, I. Ben-Zvi, I. Bigio, R.C. Fernow,
J. Fischer, A.S. Fisher, J. Gallardo, Xie Jialin, Z.Y. Jiang,
C. Pellegrini, T. Rao, J. Rogers, J. Sheehan, T. Shimada,
T.Y.F. Tsang, S. Ulc, A. Van Steenbergen, X.J. Wang,
M. Woodle, R.S. Zhang

(a) Brookhaven National Laboratory; (b) Los Alamos National Laboratory;
(c) Princeton University; (d) SUNY, Stony Brook; (e) UCLA

The following is a partial list of experiments planned for the ATF:

- Laser-grating accelerator experiment.
- Inverse free-electron laser demonstration stage.
- Inverse Čerenkov accelerator experiment.
- Visible free-electron laser.
- Nonlinear Compton scattering experiment.

Figure 1. The proposed experimental beamlines of the ATF.
Proposal for a Study of  
Laser Acceleration of Electrons  
Using Micrograting Structures  
at ATF (Phase I)  
29 October 1989

W. Chen, J. Claus, R. C. Fernow, J. Fischer,  
J. C. Gallardo, H. G. Kirk, H. Kramer, Z. Li,  
R. B. Palmer, J. Rogers, T. Srinivasan-Rao,  
T. Tsang, S. Ulc, J. Velligdan and J. Warren  
Brookhaven National Laboratory

I. Bigio, N. Kurnit and T. Shimada  
Los Alamos National Laboratory

K. T. McDonald and D. P. Russell  
Princeton University

X. Wang  
UCLA

CENTER FOR ACCELERATOR PHYSICS

BROOKHAVEN NATIONAL LABORATORY  
ASSOCIATED UNIVERSITIES, INC.  
Under Contract No DE-AC02-76CH00016 with the  
UNITED STATES DEPARTMENT OF ENERGY
Bibliography of Princeton Contributions to the ATF


Summary of DOE Support for Princeton U. at the ATF

I. Operating Expenses (1987-)
   Ongoing travel and salary support, including use of technical staff.

II. Supplement (1988-89) ............................................................... $50k
   Construction of the CCD-camera emittance monitors.

III. Supplement (1989-1990) ........................................................... $50k
   Construction of the backscattered x-ray diagnostic.

IV. Budget Request for the Fiscal Year 1991
   Construction of the nonlinear Compton scattering experiment.
   a. Pyrolitic graphite crystals ...................................................... $5k
   b. X-ray scattering chamber ..................................................... $5k
   c. Motion control for the graphite crystal and x-ray detector .......... $10k
   d. Vacuum system for the x-ray spectrometer and x-ray beam diagnostic $20k

   **Total** ................................................................................. $40k