Monte-Carlo Simulation of Laser Compton Scattered X-rays using Geant4

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Abstract

Laser Compton Scattered (LCS) X-rays are produced as a result of the interaction between accelerated electrons and a laser beam. The yield of LCS X-rays is dependent on the laser power, angle of collision between interacting particles, and the electron linear accelerator's (linac) electron beam energy and current. One of our research goals focuses on applications such as Monte-Carlo simulations of LCS X-rays using Geant4 toolkit. LCS X-rays offer much better signal-to-noise ratios for such applications. The energy of LCS X-rays is tunable, that enable element-specific analysis. Two sharp 36.5 keV and 98.4 keV LCS peaks were experimentally observed in two separate experiments based on electron beams tuned at 32 MeV and 37 MeV, that were brought in collision with the $(Power)_{peak} = 4\ GW$ Nd:YAG laser operating at 532 nm and 266 nm wavelengths. The linac was operating at 60 Hz with an electron beam pulse length of about 50 ps and a peak current of about 7 A. Whereas, we produced 34.98 keV and 98.5 keV LCS X-rays following interaction between 37 MeV electrons and 532 nm laser, and 38 MeV electrons and 266 nm laser using Geant4 Monte-Carlo simulation toolkit. The computer simulated and experimental results agree with each other and further simulations will be exploited to use Geant4 as a benchmark tool for LCS X-rays.

1.0 Introduction

1.1 Motivation

Non-invasive techniques, also known as Non Destructive Assay (NDA), are important for nuclear non-proliferation and safeguards. LCS X-rays are potentially suitable for such purposes, as well as applications in nuclear waste management and other disciplines where elemental analysis is important. The goal of this research was to demonstrate the potential of LCS as a tool to identify and quantify the reference foils' elemental content, which in future will be extended to identify fissionable material. Further, we simulated the production of LCS X-rays using Geant4 Monte-Carlo toolkit. The motivation of this paper is to demonstrate and compare simulations with the experiment performed at the Idaho Accelerator Center (IAC).

1.2 Problem Statement

Traditionally, low energy X-rays, at the tens to hundreds of kilo electron volts (keV), are produced by impinging beam of electrons at the kilo volts (kV) energy scale on a high-Z target, such as tungsten, inside vacuumed X-ray tube. The resulting X-ray spectrum is continuous because of the deflection of fast moving incoming monoenergetic electrons in the vicinity of the target nuclei, emitting radiation isotropically in all directions [1]. Figure 1.1(a) shows a typical continuous X-ray spectra from a tube operating at three different peak voltages with the same current. Even though, X-ray intensity is directly related to the tube voltage, the continuous nature of the spectrum is not desirable for imaging purposes because it deteriorates the contrast in an image.

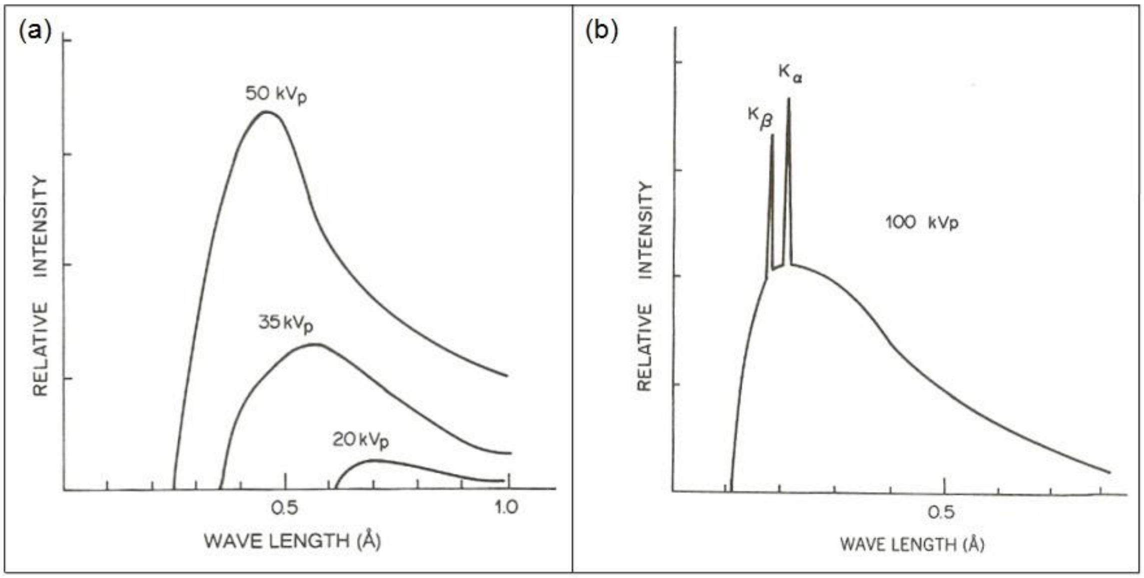

Figure 1.1. Continuous X-ray spectrum at (a) three different peak voltages and (b) at a voltage high enough to eject an electron from the K shell in the target atom, the additional characteristic K_α and K_β X-ray lines appears as a result of the emission of these discrete X-rays. [1]

If the tube voltage is sufficient (figure 1.1(b)), electrons striking the target can eject electrons from the target atoms so discrete X-rays, also known as K X-rays, are also produced that are emitted when electrons from higher shells fill the inner-shell vacancies. These discrete X-ray emission lines are also not desirable in addition to continuous, also known as white noise, and isotropic X-ray radiation.

To eliminate white noise from the X-ray spectrum, we propose to produce monochromatic, or loosely speaking quasi-monochromatic, and polarized X-rays at the IAC using short pulsed electron linear accelerator (linac) and Nd:YAG laser.

2.0 Theoretical Description

Laser Compton Scattered (LCS) X-rays are produced as a result of the interaction between accelerated electrons and a laser beam (figure 2.1). The relativistic electrons scatter low energy laser photons to a higher energy and hence also referred to as incoherent or Compton scattering of low energy laser photons. The direction of the back scattered LCS X-rays is governed by the direction of the electron beam, with divergence on the order of 1/γ, where γ is defined as the ratio of the incoming electron beam energy to the rest mass energy of an electron. [2]

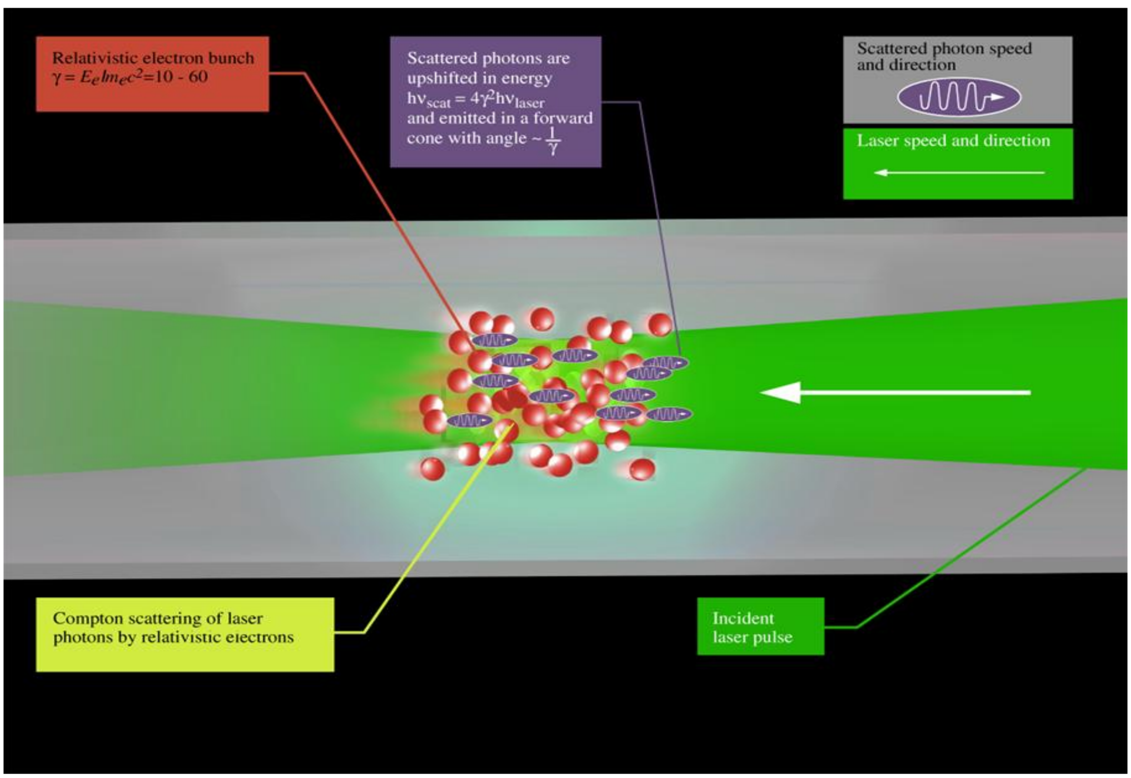

Figure 2.1. Production of LCS X-rays as a result of the interaction between relativistic electrons and a laser beam.

The yield of LCS X-rays is dependent on the laser power, angle of collision between interacting particles, and the electron linear accelerator's (linac) electron beam energy and current. The energy gained by the backscattered X-ray photons is as follows [2]:

$$E_\gamma = \frac{4\gamma^2 E_L}{1+\gamma^2\theta^2} \tag{2.1}$$

Where, $\gamma = \frac{E_e}{E_0}$, E_e is the electron beam's energy and E_0 is the rest mass energy of an electron, E_L is the laser beam's energy in electron volts (eV), and θ is the LCS X-rays emission angle in radians. The maximum Compton back-scattered photon energy can be estimated from equation 2.1 by assuming an approximate head-on collision between electrons and the laser:

$$\left(E_\gamma\right)_{Max} \approx 4\gamma^2 E_L \tag{2.2}$$

3.0 Methods and Materials

Geant4 is a Monte-Carlo simulation toolkit for the simulation of the passage of particles through matter and an ideal tool to optimize experimental parameters [3]. We used Geant4 to simulate the production of LCS X-rays, Compton process in PhysicsList, by colliding electron pencil-beam with pencil-beam laser, photons. We “Lorentz Boosted” the incoming lab frame photons into its rest frame before colliding them with the electrons. Following Lorentz Boost, we collided the photons, now in the rest mass frame, with the electrons also in the rest mass frame, and then the resulting Compton backscattered photons (LCS X-rays) were boosted back into lab frame. Following Geant4 classes were edited to specify Lorentz Boost object and figure 3.1 demonstrates the production of LCS X-rays following interaction between pencil-beam electrons and pencil-beam laser:

PrimaryGeneratorAction Class

```
electronGun = new G4ParticleGun(n_particle);
laserGun = new G4ParticleGun(n_particle);

 …

p4eRestFrame = new G4LorentzVector;
p4gammaRestFrame = new G4LorentzVector;

p4eRestFrame->setPx(0);
p4eRestFrame->setPy(0);


//32MeV Electron Beam
G4double ElectronRestFrameBeta = -0.99987252389;//32 MeV electron
p4eRestFrame->setPz(32.0*MeV);
p4eRestFrame->setE(32.0040797556*MeV);


//37MeV Electron Beam
//G4double ElectronRestFrameBeta = -0.99990464439;
//p4eRestFrame->setPz(37.0*MeV);
//p4eRestFrame->setE(37.0035284939*MeV);
```

```
  //38MeV Electron Beam
  //G4double ElectronRestFrameBeta = -0.9999095964;
  //p4eRestFrame->setPz(38.0*MeV);
  //p4eRestFrame->setE(38.0034356473*MeV);


  p4gammaRestFrame->setPx(0);
  p4gammaRestFrame->setPy(0);


  //----//values for 266nm(using 133nm, i.e, 4rd harmonic of
fundamental)  laser---
  //p4gammaRestFrame->setPz(-8.928*eV);
  //p4gammaRestFrame->setE(8.928*eV);


  //----//values for 532nm(using 266nm, i.e, 3rd harmonic of
fundamental)  laser---
  p4gammaRestFrame->setPz(-4.464*eV);
  p4gammaRestFrame->setE(4.464*eV);

  //----//values for 1064nm (using 532nm, i.e, 2nd harmonic of
fundamental) laser---
  //p4gammaRestFrame->setPz(-2.236*eV);
  //p4gammaRestFrame->setPz(2.236*eV); //wrong value
  //p4gammaRestFrame->setE(2.236*eV);


  p4gammaRestFrame->boostZ(ElectronRestFrameBeta);


  electronGun->SetParticleDefinition(particle_electron);
  //electronGun->SetParticlePolarization(G4ThreeVector(0.,0.,-1));
  electronGun->SetParticleMomentumDirection(G4ThreeVector(0.,0.,-1.));
  electronGun->SetParticleEnergy( p4eRestFrame->e());

  laserGun->SetParticleDefinition(particle_laser);

  laserGun-
>SetParticleMomentumDirection(G4ThreeVector(0.,0.,1.));//head-on
  laserGun->SetParticleEnergy(p4gammaRestFrame->e());


}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OO
ooo......

ExN02PrimaryGeneratorAction::~ExN02PrimaryGeneratorAction()
{
  delete electronGun;
  delete laserGun;
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OO
ooo......
```

```
void ExN02PrimaryGeneratorAction::GeneratePrimaries(G4Event* anEvent)
{
  G4double position = -0.5*(myDetector->GetWorldFullLength());
  //laserGun-
>SetParticlePosition(G4ThreeVector(0.*cm,10.*cm,position*cm));//perpend
icular

  laserGun-
>SetParticlePosition(G4ThreeVector(0.*cm,0.*cm,position*cm));//head-on
  laserGun->GeneratePrimaryVertex(anEvent);

  electronGun->SetParticlePosition(G4ThreeVector(0.*cm, 0.*cm,-
position*cm));
  electronGun->GeneratePrimaryVertex(anEvent);

}
```

PhysicsList Class

```
if (particleName == "gamma") {

      pmanager->AddDiscreteProcess(new SyedCompton);

}
```

SteppingVerbose Class

```
if (fTrack->GetDefinition()->GetPDGEncoding()==11 && fTrack-
>GetParentID() ==1 && fTrack->GetVolume()->GetName() !="Target")
 {


      electronKE= (fTrack->GetKineticEnergy())*1000;  //KE in keV
      electronxPosition= fTrack->GetPosition().x();
      electronyPosition= fTrack->GetPosition().y();
      electronzPosition= fTrack->GetPosition().z();
      electronxMomentum=fTrack->GetMomentum().x();
      electronyMomentum=fTrack->GetMomentum().y();
      electronzMomentum=fTrack->GetMomentum().z();
      electronPDGID=fTrack->GetDefinition()->GetPDGEncoding();

      p4eLabFrame = new G4LorentzVector;
      p4eLabFrame->setPx(fTrack->GetMomentum().x());
      p4eLabFrame->setPy(fTrack->GetMomentum().y());
      p4eLabFrame->setPz(fTrack->GetMomentum().z());
      p4eLabFrame->setE((fTrack->GetKineticEnergy())*1000);
      //p4eLabFrame->boostZ(0.9996737585);//20 MeV Electrons
      p4eLabFrame->boostZ(0.99987252389);//32 MeV Electrons
      //p4eLabFrame->boostZ(0.99990464439);//37 MeV Electrons
      //p4eLabFrame->boostZ(0.9999095964);//38 MeV Electrons

      tempBuffer[14] = p4eLabFrame->e();
      tempBuffer[15] = fTrack->GetMomentum().x();
      tempBuffer[16] = fTrack->GetMomentum().y();
      tempBuffer[17] = fTrack->GetMomentum().z();
```

```
      if(tempFlag == 1){

        if(electronKE != 0.0 /*&& electronxPosition != 0.0 &&
electronyPosition != 0.0 && electronzPosition != 0.0 &&
electronxMomentum!= 0.0 && electronyMomentum!= 0.0 &&
electronzMomentum!= 0.0 */){
        outfile
          << tempBuffer[0] <<"   "
          << tempBuffer[1] << "   "
          << tempBuffer[2] << "   "
          << tempBuffer[3] << "   "
          << tempBuffer[4] << "   "
          << tempBuffer[5] << "   "
          << tempBuffer[6] << "   "
          << tempBuffer[7] << "   "
          << tempBuffer[8] << "   "
          << tempBuffer[9]  << " "
            << tempBuffer[10] << " "
            << tempBuffer[11] << " "
            << tempBuffer[12] << " "
            << tempBuffer[13] << " "


          << electronKE << "   "
          << electronxPosition << "   "
          << electronyPosition << "   "
          << electronzPosition << "   "
          << electronxMomentum << "   "
          << electronyMomentum << "   "
          << electronzMomentum << "   "
            << tempBuffer[14] << " "
            << tempBuffer[15] << " "
            << tempBuffer[16] << " "
            << tempBuffer[17] << " "
          << electronPDGID << "   "
          << G4endl;
        //ComptonEventCounter = 0;
      }
      }
      tempFlag = 0;
  }


  if (fTrack->GetDefinition()->GetPDGEncoding()==22 && /*fStep-
>GetPostStepPoint()->GetProcessDefinedStep()->GetProcessName() ==
"compt" fStep->GetPostStepPoint()->GetProcessDefinedStep()-
>GetProcessName() == "LowEnCompton" &&*/ fTrack->GetVolume()->GetName()
!="Target")
{

      ComptonEventCounter+=1.0;     //to solve contatenation issue

      tempBuffer[0] = ComptonEventTrigger;
      tempBuffer[1] = ComptonEventCounter;
      tempBuffer[3] = fTrack->GetPosition().x();
      tempBuffer[4] = fTrack->GetPosition().y();
      tempBuffer[5] = fTrack->GetPosition().z();
```

```
        tempBuffer[2] = (fTrack->GetKineticEnergy())*1000;
        tempBuffer[6] = fTrack->GetMomentum().x();
        tempBuffer[7] = fTrack->GetMomentum().y();
        tempBuffer[8] = fTrack->GetMomentum().z();

        p4gammaLabFrame = new G4LorentzVector;
        p4gammaLabFrame->setPx(fTrack->GetMomentum().x());
        p4gammaLabFrame->setPy(fTrack->GetMomentum().y());
        p4gammaLabFrame->setPz(fTrack->GetMomentum().z());
        p4gammaLabFrame->setE((fTrack->GetKineticEnergy())*1000);
        //p4gammaLabFrame->boostZ(0.9996737585);//20 MeV Electrons
        p4gammaLabFrame->boostZ(0.99987252389);//32 MeV Electrons
        //p4gammaLabFrame->boostZ(0.99990464439);//37 MeV Electrons
        //p4gammaLabFrame->boostZ(0.9999095964);//38 MeV Electrons

        tempBuffer[9]  = p4gammaLabFrame->e();
        tempBuffer[10] = fTrack->GetMomentum().x();
        tempBuffer[11] = fTrack->GetMomentum().y();
        tempBuffer[12] = fTrack->GetMomentum().z();
        tempBuffer[13] = fTrack->GetDefinition()->GetPDGEncoding();

        tempFlag = 1;
}
```

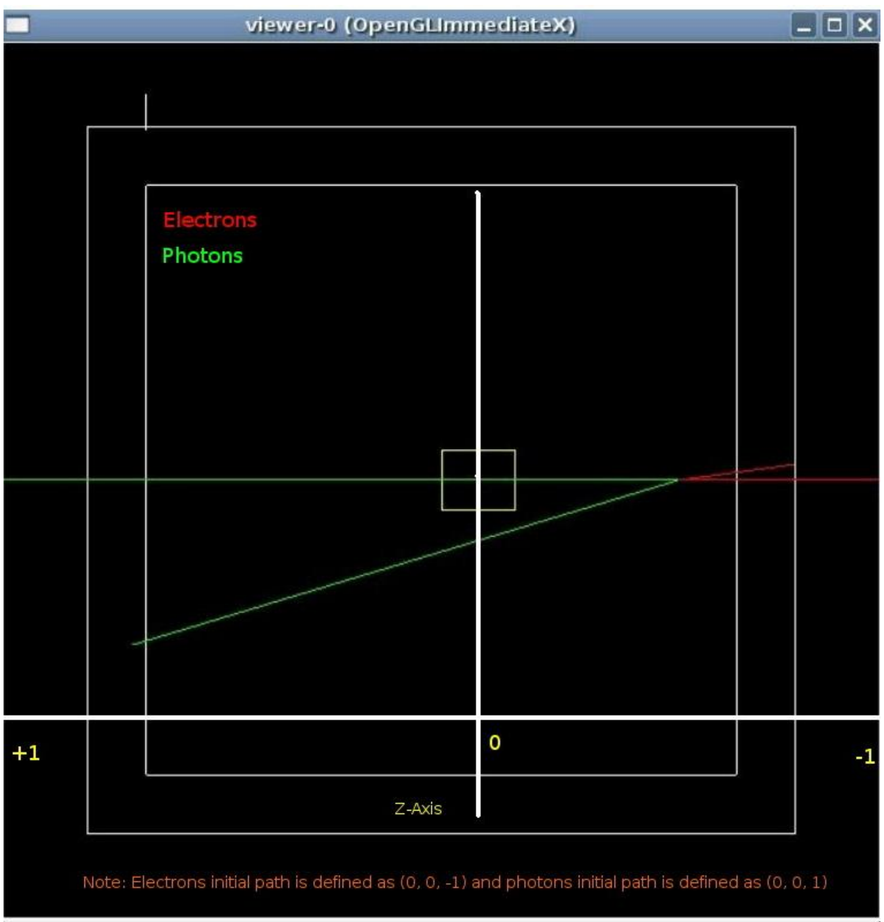

Figure 3.1. Geant4 simulation graphical view of the interaction between pencil-beam electrons (red) and pencil-beam laser (green).

4.0 Results

4.1 Monte-Carlo Simulation

LCS X-rays are produced when accelerated electrons collide with a pulsed laser. The laser and electron beam collision time is synchronized to produce backscattered LCS X-rays. Figures 4.1 through 4.3 demonstrates computer simulated, Monte-Carlo simulation in geant4 simulation toolkit [3], an ideal monochromatic LCS X-rays with peak energy at 35.05 keV with 34.98 keV rms, its angular distribution, and X-ray energy vs. angle, plots produced as a result of interaction between 32 MeV electrons and 532 nm laser. Likewise, similar results are plotted for the case of 38 MeV electrons and 266 nm laser in figures 4.4 through 4.6.

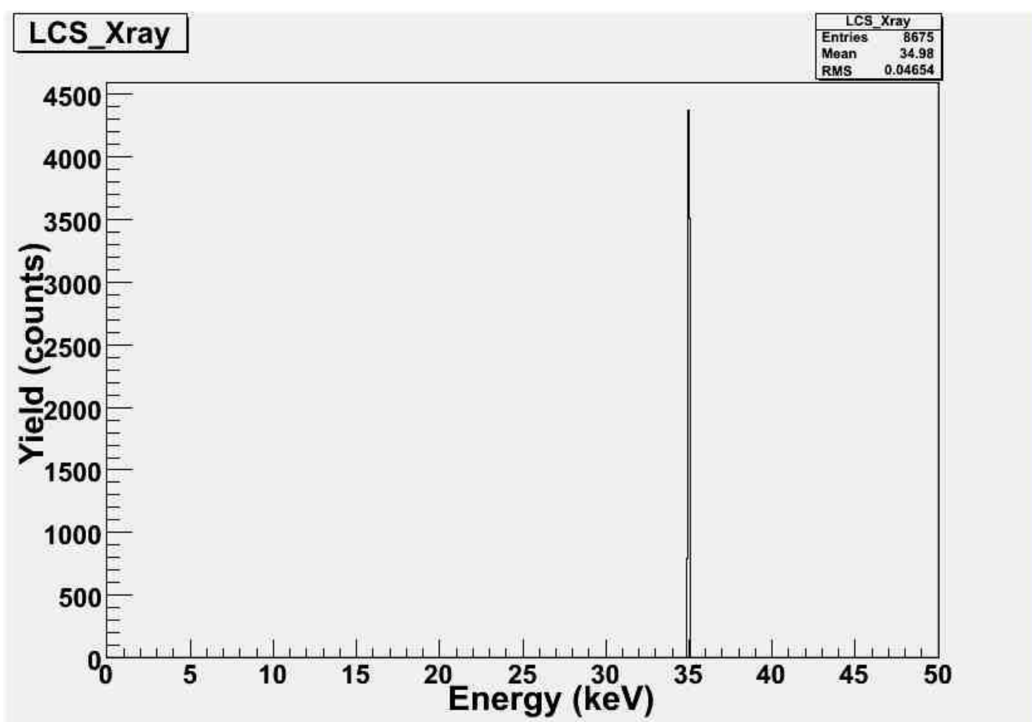

Figure 4.1. 34.98 keV LCS X-rays produced as a result of interaction between 32 MeV electrons and 532 nm laser.

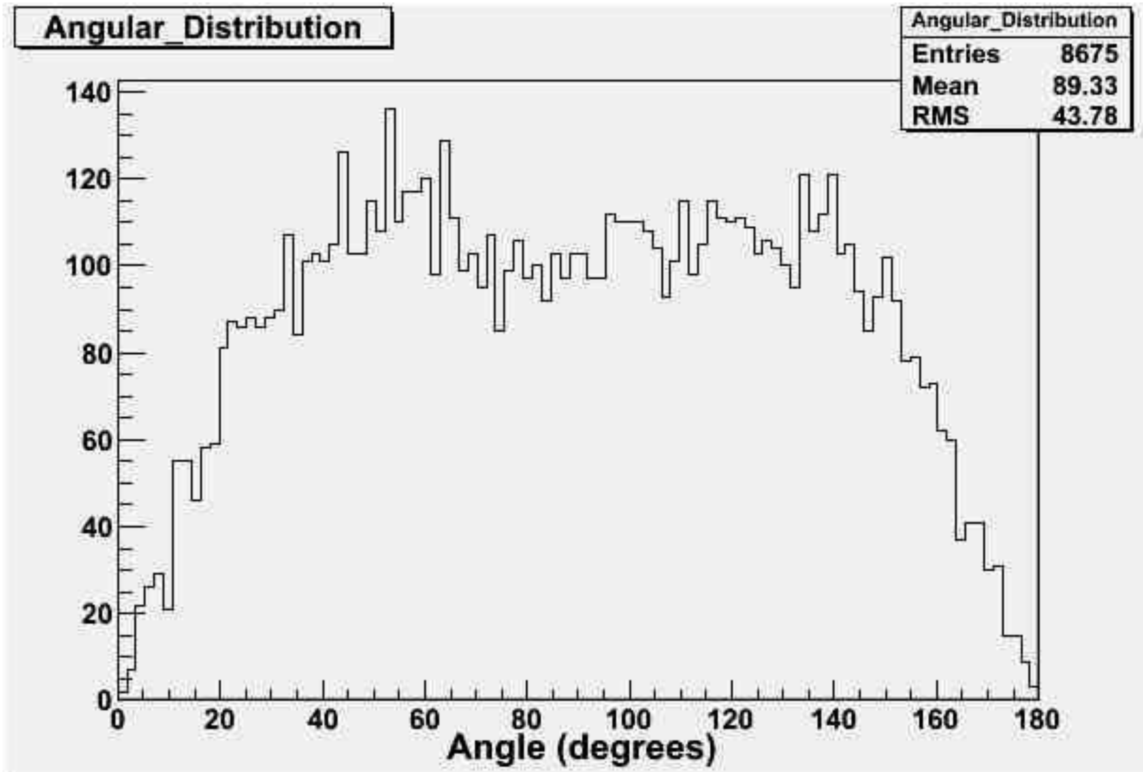

Figure 4.2. Angular distribution of 34.98 keV rms LCS X-rays produced as a result of interaction between 32 MeV electrons and 532 nm laser.

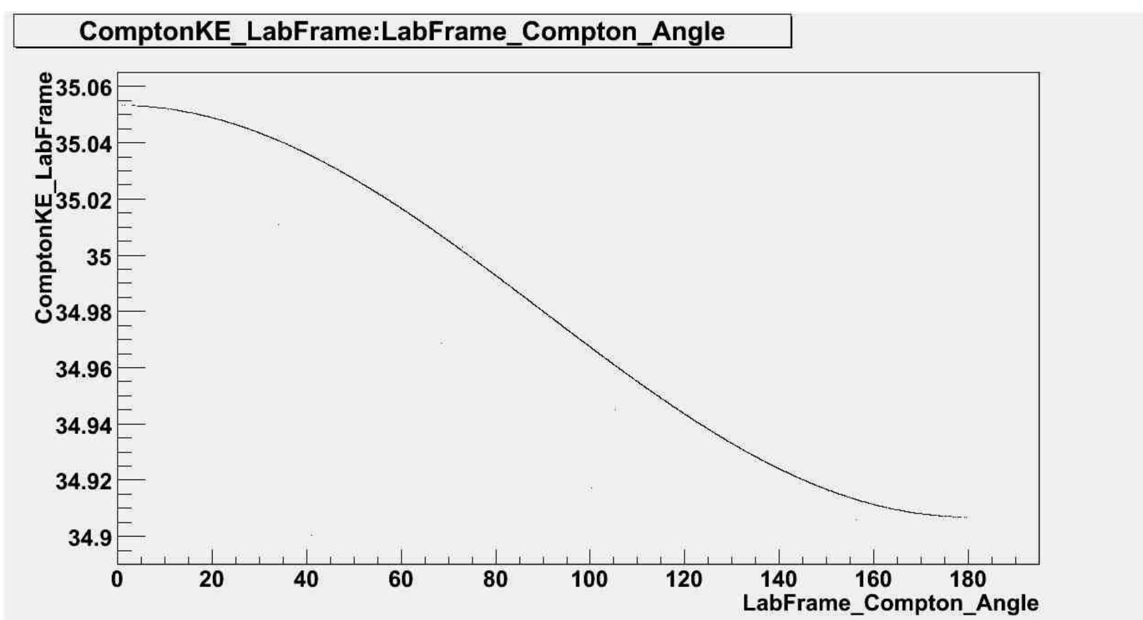

Figure 4.3. X-ray energy vs. angle (in degrees) plot for 34.98 keV rms LCS X-rays produced as a result of interaction between 32 MeV electrons and 532 nm laser.

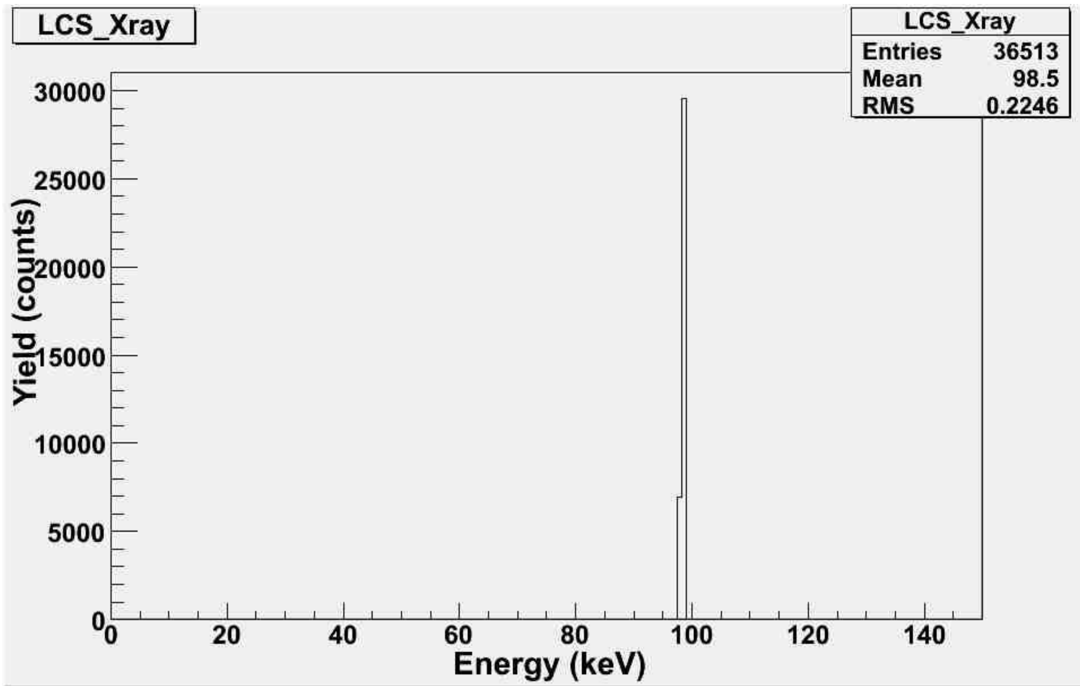

Figure 4.4. 98.5 keV LCS X-rays produced as a result of interaction between 38 MeV electrons and 266 nm laser.

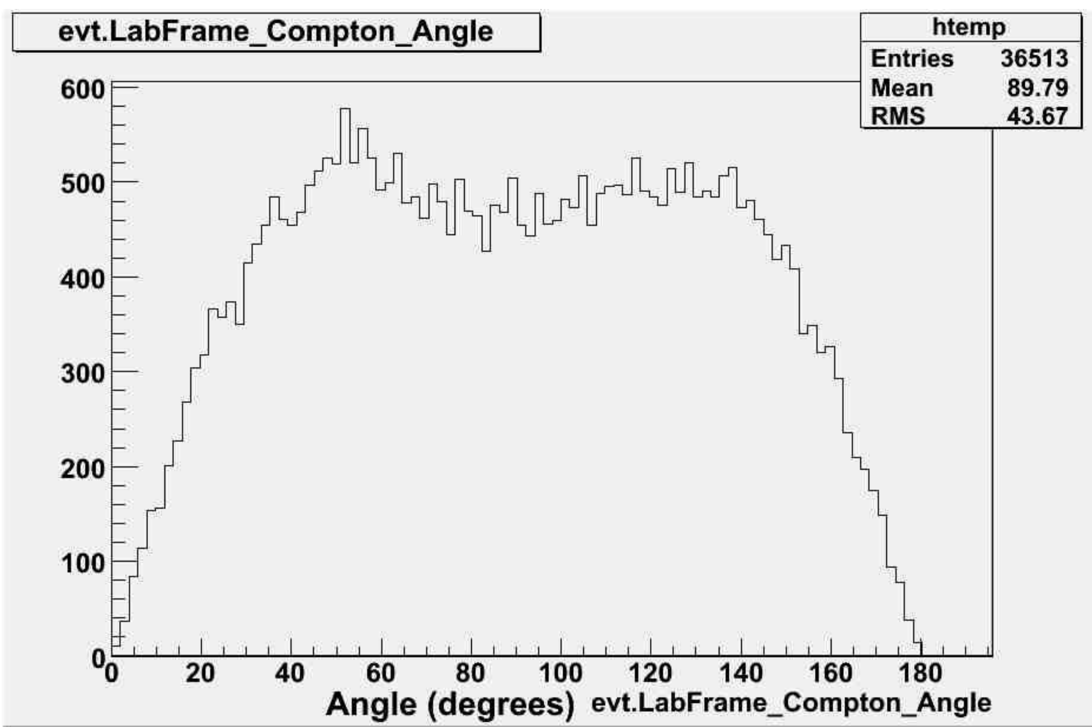

Figure 4.5. Angular distribution of 98.5 keV rms LCS X-rays produced as a result of interaction between 38 MeV electrons and 266 nm laser.

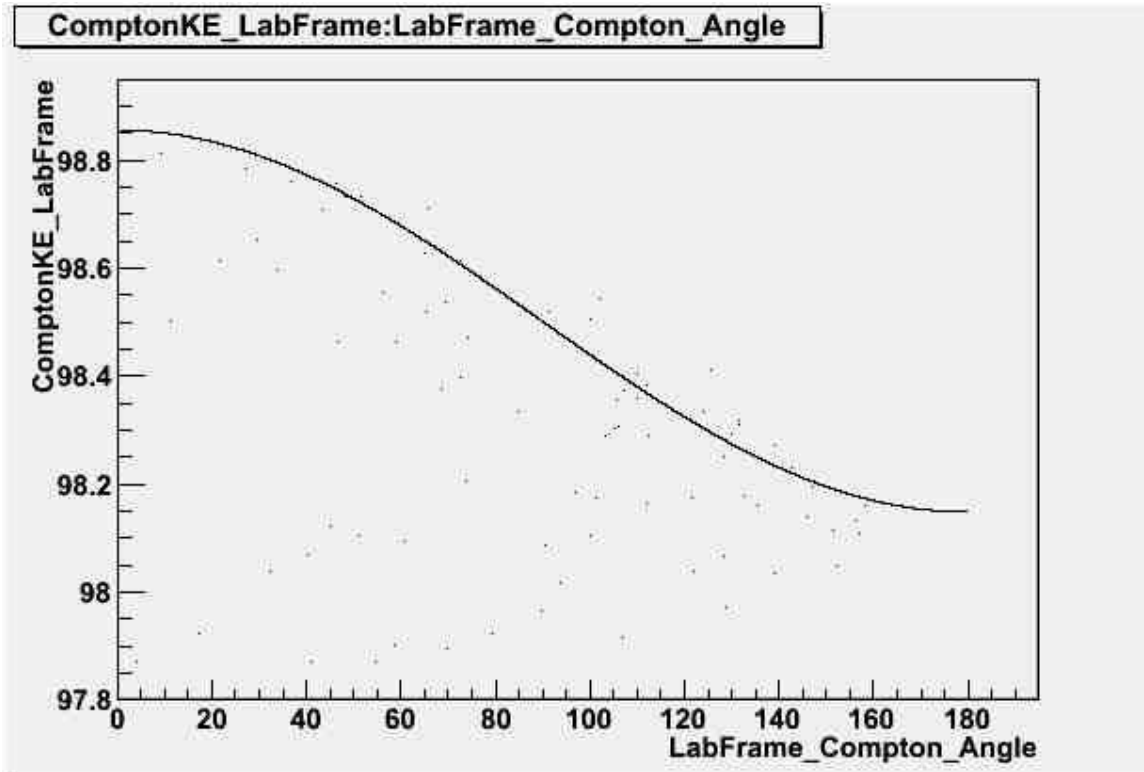

Figure 4.6. X-ray energy vs. angle (in degrees) plot for 98.5 keV rms LCS X-rays produced as a result of interaction between 38 MeV electrons and 266 nm laser.

4.2 <u>The Experiment</u>

Experimentally, a 44 MeV short pulse electron linac with 50 ps pulse width, 7 A peak current, and 60 Hz pulse repetition rate was tuned to operate at approximately 32 and 37 MeV. The energy spread in the electron beam was approximately between 1-2%. We brought a Nd:YAG laser of ~100 μm root mean square (rms) spot size operating at 4 GW peak power into an approximate head-on collision with the electron beam of ~3 mm rms. Figure 4.7 shows the electron and laser beam path in the experimental cell and the accelerator hall.

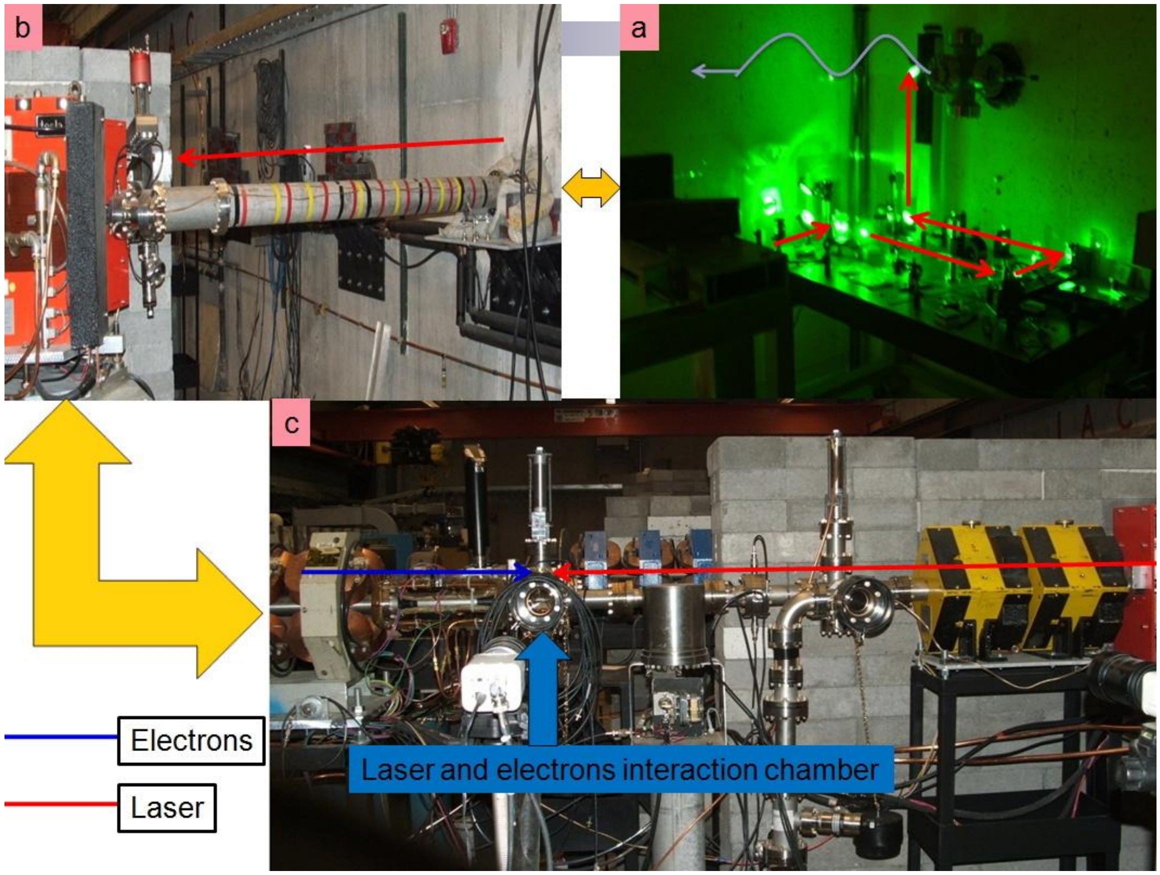

Figure 4.7. IAC experimental facility for LCS experiments. (a) Experimental cell, (b, c) Accelerator Hall.

Figures 4.8 and 4.9 shows the back-scattered quasi-monochromatic, because of the divergence in the incoming electron beam, Compton photo peaks from the Nd:YAG laser operating at 532 nm (green) and 266 nm (UV) were approximately 36.5 keV and 98.4 keV. The observed pile-ups in LCS spectra are due to much larger dead-time in the HPGe detectors compared to the only 50 ps electron beam pulse length of the linac that was operating at a 60 Hz repetition rate.

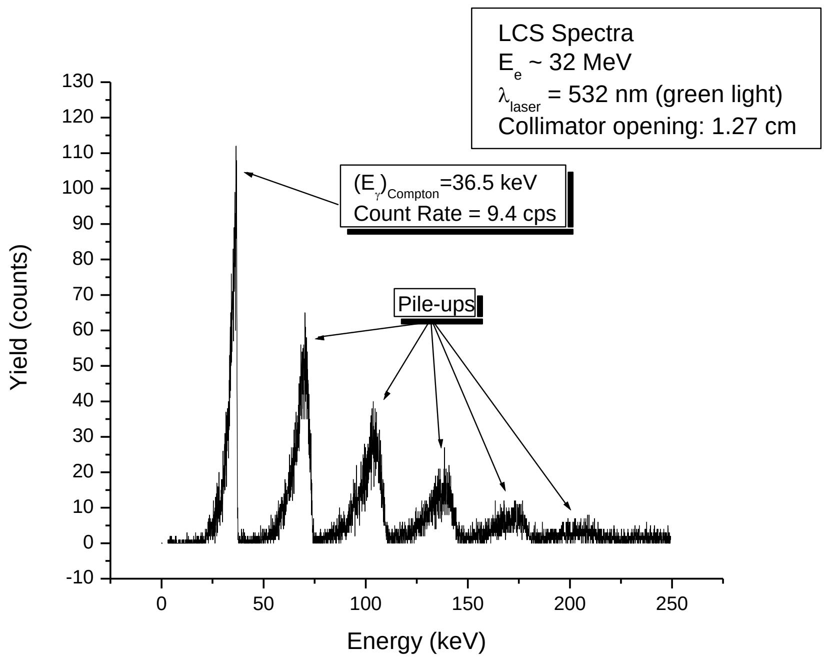

Figure 4.8. LCS spectra of 36.5 keV following the interaction between the ~32 MeV electron beam and the 532 nm laser.

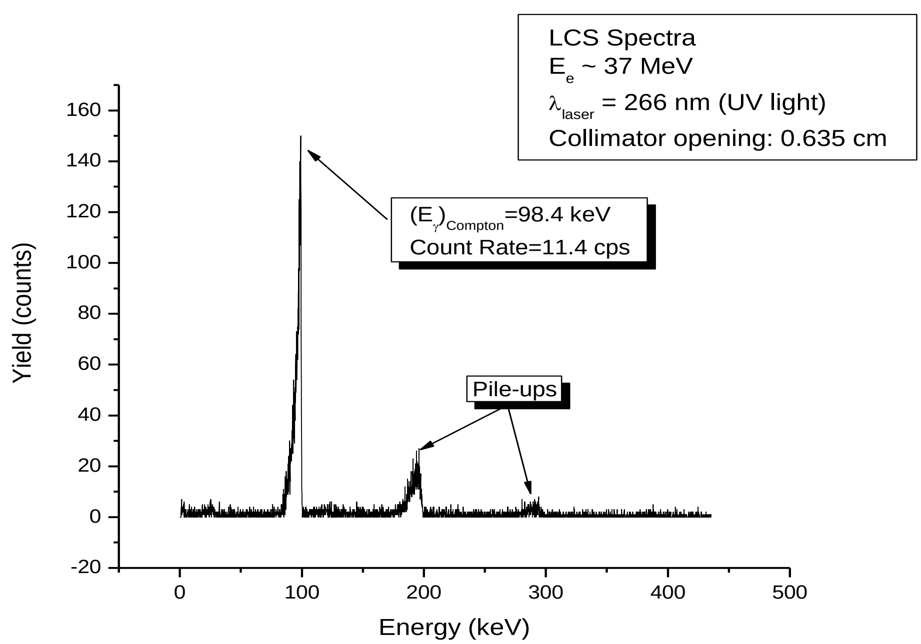

Figure 4.9. LCS spectra of 98.4 keV following the interaction between the ~37 MeV electron beam and the 266 nm laser.

5.0 Conclusions

We produced LCS X-rays of 36.5 keV peak energy as a result of the interaction between the relativistic electron beam of ~32 MeV and the 532 nm (green) Nd:YAG laser. Similarly, LCS X-rays of 98.4 keV peak energy were produced upon the interaction between ~ 37 MeV electrons and the 266 nm (UV) Nd:YAG laser. Whereas, we produced 34.98 keV and 98.5 keV LCS X-rays following interaction between 37 MeV electrons and 532 nm laser, and 38 MeV electrons and 266 nm laser using Geant4 Monte-Carlo simulation toolkit.

Our future work will focus on further exploiting Geant4 by making and using Gaussian distribution of the electron beam to collide with the laser. We also plan to compare LCS X-ray yield verses electron beam current.

References

[1.] Turner J. E., Atoms, *Radiation, and Radiation Protection*, 2nd Edition, New York: John Wiley & Sons, pp 40-45, 1995

[2.] Chouffani K., Wells D., Harmon F., Jones J., & Lancaster G., *Laser-Compton scattering from a 20 MeV electron beam*, Nuclear Instruments and Methods in Physics Research A, vol. 495, pp 95-106, 2002

[3.] http://www.geant4.org/geant4/, 2008