Construction of a Novel X Ray Generator

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ABSTRACT

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We discuss the designs and procedures for a novel tabletop x-ray generator. The generator is a modification of well-known x-ray generating techniques. Instead of a thermionic cathode simply ejecting electrons into an anode, a short laser pulse ejects electrons from a photocathode and an RF cavity will be incorporated to compress the electron bunches. The generator will produce high flux, short pulse x-rays to complement the LCLS. Special consideration is given to the preparation and behavior of the photocathode.

INTRODUCTION

Since their discovery over a century ago, x-rays have been instrumental in studying materials. We have since developed many different types of x-ray generators to serve our particular needs, from the classic Röntgen design all the way to the LCLS. There are many parameters that go into an x-ray generator: pulse length, brightness, coherence, cost, etc. Our project is aimed towards filling a niche in the generating world. It will, upon completion, create sub-picosecond x-ray pulses at 8 keV. These x-ray pulses will be of short enough duration and wavelength to be able to study very small, very fast events such as atomic vibrations or molecular bond breaking.

The LCLS also provides these capabilities. However, many experiments may not require the high flux that comes with the LCLS [1] and may instead prefer the high repetition rate offered by our design for a high signal-to-noise ratio. Also, as the LCLS will be in very high demand, this source will provide a machine to test ideas and train students and post-docs. The machine, while providing similar average flux typically used in kHz laser experiments on third generation synchrotron sources (but at much higher repetition rates), will be small enough to fit on a tabletop and relatively inexpensive to build. The basic design is very similar in principle to Röntgen's original setup.

We will produce our electrons with a gallium arsenide (GaAs) photocathode that has been coated with cesium[2]. We will excite the photocathode with a 515 nm laser pulse at 119 MHz. This will cause bursts of electrons to be released from the cathode via the photoelectric effect[3]. The freed electron bunches will then be accelerated by a potential difference towards a copper anode, where the electrons will be stopped and emit x-ray radiation via Bremsstrahlung and line emission. These are the fundamentals of the project that have been repeated many times over.

Our electron gun, however, will also feature an RF cavity. This cavity will cause the elec-

trons in the gun to bunch much more compactly. When the bunches strike the anode target, they will become a source of x-rays that is both brighter and shorter in pulse length. The x-rays will be particularly useful to PULSE scientists for studying areas such as phonon dynamics, molecular alignment, chemical dynamics, thermal transport, and energy conversion in condensed phase.

MATERIALS AND METHODS

Our x-ray generator will utilize a 50 kV, 1 mA electron gun to produce its x-rays. The very basic principles of this, elaborated upon in the introduction of the paper, are extremely well-known and have been used for over 100 years now.

The design of our generator must include a preparation area specifically for the photocathode. For the best electron gun, we need the quantum efficiency of the cathode to be as high as possible. The quantum efficiency is defined as the number of electrons produced per photon. The simplest way to calculate this is with the formula

$$QE = \frac{I \times e}{P \times h \times \nu} \quad (1)$$

where I is the current, e is the elementary charge, P is the power of the laser, h is Planck's constant, and ν is the laser frequency. The preparation process to achieve this is very delicate and has many requirements if it is to be done successfully.

An ultra-high vacuum (UHV) ($<10^{-11}$ Torr) environment is required to prepare and preserve a GaAs target. We want this vacuum to be not only extremely low pressure but also clean, meaning that we must use multiple types of pumps to meet the requirements. In the main vacuum chamber, we need both an ion pump and a non-evaporable getter pump. The ion pump ionizes the gases in the vacuum and then uses a potential difference to accelerate them towards an anode to remove them from the chamber. Because it has no moving parts,

there is no lubrication needed and the entire process is very clean. Ion pumps are also capable of reaching UHV pressures. The getter pump is housed in the ion pump and acts as a sort of sponge that can very efficiently remove certain chemicals, particularly hydrogen, from the vacuum when bundled with the ion pump. It also has no moving parts and requires no power source, making it a very clean way to create a vacuum. This pump removes the need for a titanium sublimation pump, which requires that a surface be surrendered to depositing the titanium that cleans the vacuum.

Reaching UHV pressures requires a very, very long time to pump (on the order of weeks), so we prefer not to break the vacuum every time we need to switch samples. This means that we require a loadlock system to load the samples. A loadlock is very similar to an airlock. It is a very small chamber that we may isolate from the main vacuum via gate valve, bring up to atmospheric pressure, load in a new, chemically cleaned sample, and then evacuate back to UHV pressures to drastically reduce the amount of time pumping is needed.

After the sample has been loaded successfully, the gate valve to the loadlock system is opened and the sample is moved from the loadlock system into the main vacuum chamber, where it is heat cleaned on a molybdenum surface. The sample is brought to 500-550 C to remove any impurities on the sample. To prevent damage to the sample transporter, it is designed as a fork. This allows the heater to be raised from below the sample to support it and the transporter to withdraw from the preparation chamber during activation.

Because of the vacuum and high temperatures, great care must be taken choosing materials in the system to lessen contamination from outgassing, or the creation of embedded gases in a material when the material is exposed to a vacuum. This is why the GaAs must be seated on molybdenum instead of stainless steel. It also has implications in the types of seals that can be used. All valves must be 100% metal. Many valves use a Viton seal that is unacceptable because of the high amounts of organic molecules that outgas from it.

Once the sample has been heat cleaned, it is time to cesiate it. Cesium creates a bias

within the photocathode that allows the electrons to be brought closer to the surface and more easily freed through the photoelectric effect. To do this, we run a current through a specially designed Alkali Metal Dispenser (AMD) that disperses cesium onto the sample while shining both a lamp and a laser on the sample. We must shine light on the GaAs to make sure that the cesiating is actually happening. The lamp is necessary because it takes several minutes for the cesium to build up enough to show a change due to the laser. When the advantages gained due to pure cesium begin to wane, NF_3 is added, which further increases the QE. After the sample has gone through this entire process, the QE begins to decrease with time.

Once we have reached the maximum possible QE, we are ready to load the target into the electron gun. We will transfer it into a second chamber isolated from the preparation chamber (to prevent contamination from the NF_3 or cesium). It is at this point that several design details must be considered. We want this chamber to be the source of electrons for the x-ray generator. We also want the x-rays to move parallel to the tabletop. There are three possible ways to achieve this goal.

First, we could leave the sample horizontal and fire the laser vertically, creating a vertical stream of electrons. We could then use a large dipole magnet to bend the electrons 90° to horizontal (Fig. 1c). However, this adds dispersion that can be difficult to compensate when trying to generate short pulses.

We could also rotate the sample to the vertical position, leaving us with two ways to produce electrons. We could fire the laser into the GaAs, creating a stream of electrons along the same path that the laser and its reflection follow. We would then need to find some way to separate the laser from the electrons. We could either send the laser in at a small deviation from the normal or use a small bending magnet to produce some divergence of the electrons from the laser (Fig. 1a).

The last option is more difficult materially but less complicated in the setup. If the thin

GaAs sample is grown on Gallium Phosphide (GaP) substrate, the laser can be fired into the sample with the electrons emitting from the opposite side of the sample. The GaP is transparent to the laser, but will prevent the electrons from escaping on the less desirable side of the sample. This way, the whole setup can be done in a line with no bending or angles (Fig. 1b).

We are sure that we will be using one of the last two methods. Thus, we must design a way to move the sample from the horizontal to vertical position. Our sample transporter will be a magnetically driven linear transporter with rotation capabilities around one axis parallel to transport. The photocathode must end up in contact with a negative high voltage supply in order to set up the correct bias for acceleration to the anode and RF cavity. This means that there must be no electrical contact between the photocathode and the chamber. If there was such contact, the entire chamber would become negatively biased, no acceleration would occur, and a potentially dangerous situation would be created.

After the photocathode has been prepared, we can measure its QE. The QE decays over time. Because time was limited to measure this decay, we approximate the results by taking an approximation

$$QE = QE_0 e^{-\frac{t}{\tau}} \approx QE_0 (1 - \frac{t}{\tau}). \quad (2)$$

This will allow us to do a linear fit of the decay data as long as $t \ll \tau$ and come up with an approximate lifetime. We may also put filters in front of the laser to measure the dependence of the photocurrent (and QE) on laser power. The current was measured instantaneously on a digital nanoammeter and over time with an analog voltmeter.

RESULTS

Over the summer, we have specified the vast majority of parts for the first stages of the x-ray generator described in this paper. The loadlock, preparation chamber, and electron source have been designed with only minor details remaining (Fig. 2). The details of the chamber are fairly standard.

We have been allowed access to a similar design, where we were prepared a cathode and measure its quantum efficiency to be 13%, sufficient for production of 1 mA current given the laser we intend to use (assuming that there is no saturation at higher powers). Further tests have determined that the dependence of the photocurrent with the power of the laser is roughly linear, indicating that the QE is proportional to the laser power. How exactly this dependence goes is unclear at the time; the photocurrent oscillates on the order of minutes, incorporating a systematic error into any series of measurements that naturally took several minutes to complete and introducing lots of scatter to the data (Fig. 3). An interesting observation of the data can be easily seen by paying special attention to the three lines that were measured up to full power. The general trend of the other lines is that the later the measurement was taken, the shallower the slope of the line was. This decay occurred much faster than the observed decay when the laser was heavily filtered (1% transmission). However, the three lines mentioned earlier were measured several hours after the others. The photocurrent obviously recovered and then degraded again upon observation. This may be due to faster decay under higher intensity lasers. The decay of the photocurrent under 1% intensity has a half-life of approximately 2.63 days (Fig. 4). More measurements are in progress with higher intensities. The cause of the periodicity of the photocurrent is also of interest.

DISCUSSION AND CONCLUSIONS

Because this portion of the x-ray generator is so similar to the design we have been allowed to practice on, there is a high probability that this part of the generator will function well and we have high confidence that it will produce the required current for the generator. Several challenges have been overcome, the project is falling within the expected price range, our test chamber is performing as expected, and we expect the project to be a success and a valuable tool for PULSE in the future.

We have also uncovered several properties that will become very important, such as the long- and short-term behavior of the photocurrent and the basic dependence of the photocurrent on laser power. These studies have also unveiled several interesting behaviors to analyze with more sophisticated equipment and techniques that simply were not available in the time frame of the initial studies.

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FIGURES

Figure 1: Different setups for the electron gun.

Figure 2: Basic design of a preparation chamber

Figure 3: Photocurrent vs. % transmission of a 1 mW laser.

Figure 4: Decay of a photocurrent at 1% transmission of a 1 mW laser.