Conceptual Design of a Novel Instrument for Producing Intense Pulses of 10 ps X-rays for Ultra-Fast Fluorescence Measurements[1]

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Abstract

We report a conceptual design of a novel bench-top device for producing intense, fast pulses of x-rays with 10 ps fwhm (full-width at half-maximum) x-ray pulse width, 120 keV maximum energy, 100 kHz repetition rate, and 1 A peak current onto the x-ray anode. The device includes three sections: (1) an electron gun that generates 5 ns wide pulses of electrons; (2) solenoidal magnetic lenses and rectangular deflection plates that focus the electrons onto an aperture plate and sweep the pulsed beam past the slit aperture, respectively; and (3) a tungsten anode onto which the post-aperture electrons are focused, producing x-ray pulses. Solenoidal magnetic lenses with a current density of 150 A•turns/cm^2 focus the 120 keV electron beam to a spot diameter of 0.32 mm such that a deflection plate dV/dt of 10^{13} V/s (achieved with power triode circuitry) will yield x-ray pulse widths of about 10 ps. We used EGUN, an electron optics and gun design program, to simulate the electron trajectories throughout the instrument.

I. INTRODUCTION

The performance of positron emission tomography (PET) instrumentation depends heavily on the scintillator crystals used as detectors. Faster and brighter scintillators could decrease detector recovery time, improve rejection of radiation resulting from Compton scattering within the patient, and possibly even reduce detector cost. The search for new scintillators requires a means of exciting samples so that fluorescent lifetimes and spectra can be measured. Previous efforts to find better scintillators made use of an electron synchrotron in single-bunch mode to measure the x-ray excited fluorescence of over 400 compounds [1, 2], a process that was both expensive and time-consuming. More recently, a table-top device capable of producing 109 ps fwhm pulses of x-rays has been used in the search for new scintillators [3–5]. While this instrument has reduced the cost and increased the ease of making scintillation measurements, it generates peak currents of only 1 mA and produces x-rays with a maximum energy of 30 keV. Hence, the 10 ps x-ray pulse width, 1 A peak current, 120 keV maximum x-ray energy design presented in this paper represents a major improvement both in timing resolution and in the SNR of the resulting scintillation measurements. In addition, the new design maintains a fast repetition rate of 100 kHz and satisfies the important design criteria of table-top size and low cost.

II. DESIGN OVERVIEW

The x-ray source design consists of three distinct sections: (1) an electron gun that generates pulses of electrons, (2) a deflection system that sweeps the electron pulses past an aperture to chop them and thus decrease their width, and (3) an anode for generating x-rays. The first section costs approximately $100,000 (U.S.) [6], and we estimate the cost of the remainder of the instrument to be less than that same amount. Figure 1 shows the three sections of the device.

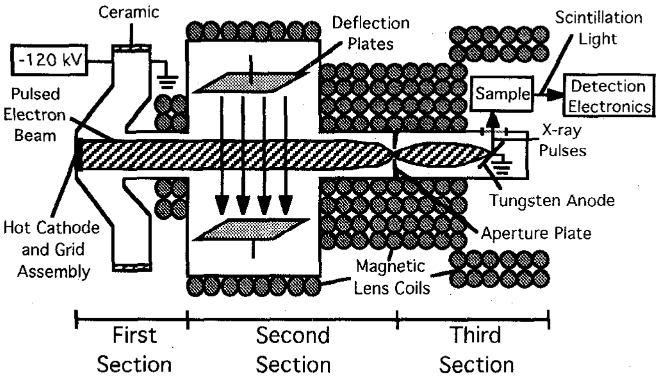

Figure 1: The three sections of the pulsed x-ray instrument, most of which is cylindrically symmetric. The instrument as shown is approximately 0.7 m long and has a radius of about 0.1 m.

A. Section 1: Electron Gun

The first stage is an electron gun which generates a beam of electrons via thermionic emission from a 1 cm^2 heated metal surface (the cathode). A grid pulsed between –400 V and +400 V is capable of completely turning off the electron beam and limits the duration of the electron pulses to approximately 5 ns. The electrons are accelerated across 120 kV—a reasonable choice considering expense and high voltage complications—and the metal walls surrounding the beam act as an electrostatic lens that focuses the electrons enough to counteract space charge repulsion and yield a nearly parallel beam of electrons upon exit from the first section. The repetition rate of the x-ray pulses is ultimately set by the rate at which the cathode grid is pulsed.

B. Section 2: Focus, Deflection, and Chopping

The second stage consists of three main components: solenoidal magnetic lens coils, a pair of deflection plates, and a plate with a 0.32 mm slit aperture. Focusing the pulsed electron beam onto the aperture plate is achieved by driving

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current in a solenoid around the instrument (i.e., outside of the vacuum) at a density of 150 A•turns/cm^2, forming a magnetic field that forces the electrons to converge to a spot diameter of about 0.32 mm despite space charge repulsion.

The two deflection plates generate a time-varying electric field that deflects the electron beam. The lower plate is held at ground potential, while a power triode [7] provides sinusoidal modulation (16 kV amplitude, 100 MHz frequency) of the upper plate to yield a maximum sweep rate of about 10^{13} V/s. The system is synchronized such that when each pulse of electrons traverses the space between the deflection plates, the upper plate is brought to ground potential exactly once, always moving from positive to negative voltage. During this zero-crossing the electron beam is swept from above the aperture to below it, producing a chopped electron pulse about 10 ps in width. The remainder of the beam is absorbed by the aperture plate, dissipated primarily as heat.

The use of deflection systems to chop electron beams to pulses on the order of 10 ps width has been reported in numerous articles [8–10], though these are generally oriented toward scanning electron microscope (SEM) applications. The beam currents are typically less than 1 nA, hence small focal spot diameters are much easier to achieve and beam sweeping via deflection plates is simpler because small spot sizes require lesser sweep speeds to achieve 10 ps pulse widths. In the design of this pulsed x-ray instrument, however, both focusing and beam sweeping proved challenging.

C. Section 3: Anode and Exit Window

The third stage involves additional magnetic lenses and a tungsten anode (at ground potential). Once again a solenoidal magnetic lens system focuses the electron beam, this time to a spot diameter of 0.45 mm on the tungsten anode. The 10 ps electron pulses thus collide with the anode over a relatively small area, in the process generating x-rays with energies up to 120 keV. These x-rays exit the instrument through a beryllium exit window and an aluminum filter. Space near the exit window must be left for a sample, which is to be contained within a quartz cuvette.

D. EGUN Electron Trajectory Simulations

Designing the metal wall geometries and the magnetic lenses for minimal focal spot sizes required careful simulation of the electron trajectories. To this end EGUN, an electron optics and gun design program, was used [11]. The program computes the trajectories of charged particles through electrostatic and magnetostatic fields, accounting for space charge repulsion, self-magnetic fields, relativistic effects, and space-charge-limited emission from the cathode surface (i.e., Child-Langmuir equation). The code is 2-D for all fields and 3-D for all particle motion, making cylindrical symmetry the best choice for this application. User-input boundary values, both Dirichlet (on which the potential is known) and Neumann (on which the normal derivative of the potential is known), are thus defined in terms of radial and z-axis coordinates. EGUN solves Poisson's equation for these boundary conditions, then differentiates the potential distribution to determine the electric field. Magnetic fields may be included by defining the location and current magnitude (in A•turns) of a series of circular coils, allowing for simulation of solenoidal magnetic lenses.

Detailed EGUN simulation results for the path of electron pulses throughout the length of the instrument are shown in Figure 2. The configuration of the electron gun section is a version of the Lawrence Berkeley National Laboratory Advanced Light Source (ALS) electron gun, modified to yield a 1.18 A beam. Even if 10% of the electrons are lost to the cathode grid and another 10% are lost to the aperture plate at the peak beam-aperture alignment, a peak anode current of 0.96 A will still be maintained. The magnetic lens coil configuration used to achieve the electron trajectories shown in Figure 2 is presented in detail in reference [12].

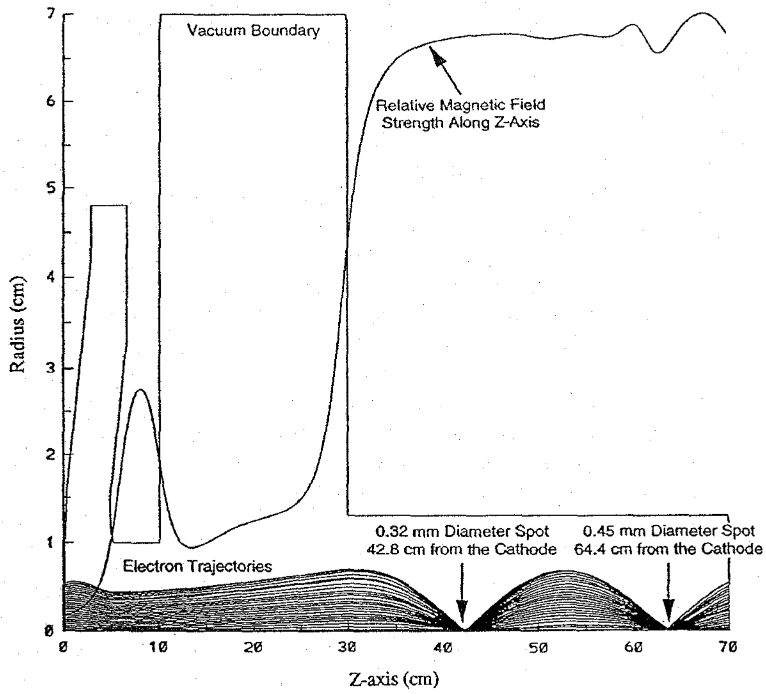

Figure 2: EGUN simulation of electron trajectories throughout the length of the instrument. The electron-emitting surface of the cathode (left side of figure) has a radius of 5.6 mm. This configuration yields a 1.18 A beam with a focal spot diameter of 0.32 mm at a distance of 43.8 cm from the cathode and a second focal spot diameter of 0.45 mm at a distance of 64.4 cm from the cathode. The deflection plates are not depicted because they do not demonstrate cylindrical symmetry, but they are located within the largest part of the instrument and centered (in the direction of the z-axis) at z = 20 cm. The plates are approximately rectangular with a z-axis length of 10.0 cm, a width of 5.0 cm, and a separation distance of 3.5 cm. The magnetic lens coils are also not shown, but the relative magnitude of the magnetic field along the length of z-axis is indicated. The best focusing is achieved when the magnetic field is kept constant for z > 30 cm, but small fluctuations are evident near z = 60 cm. These were minimized but could not be fully eliminated because the regular pattern of magnetic lens coils is disrupted by the need to leave empty space for scintillator samples near the x-ray exit window.

III. MAJOR DESIGN TRADEOFFS/LIMITATIONS

A. General Focusing Considerations

The limitations inherent in focusing a 1 A electron beam to a small spot despite significant space charge repulsion have a critical influence on the design of this device. A smaller aperture plate spot size will decrease the post-aperture electron pulse width, hence the aperture focal spot must be minimized.

Solenoidal magnetic lenses were chosen over electrostatic lenses as the primary focusing elements because they are simpler to use and because magnetic lens aberrations are generally less dominant. Greater current density in the magnetic lens coils provides stronger focusing ability, but in most magnetic lenses heat dissipation limits this density to about 150 A•turns/cm^2 [13]. Even then a combination of epoxy poured over and between the coils (to increase thermal conductivity) and/or water cooling must be employed.

Figure 3 displays EGUN simulation results for a parallel beam of electrons focused with a simple solenoidal magnetic lens configured to work well with 1 A beams. At low currents the spot diameter is limited by aberrations, though smaller spot sizes could be achieved were the lens system tailored to smaller currents. Larger currents rapidly increase the spot size, demonstrating a near-exponential dependence. Smaller spot diameters are achieved with greater acceleration voltages because the beam travels faster and hence space charge repulsion has less time in which to increase beam size.

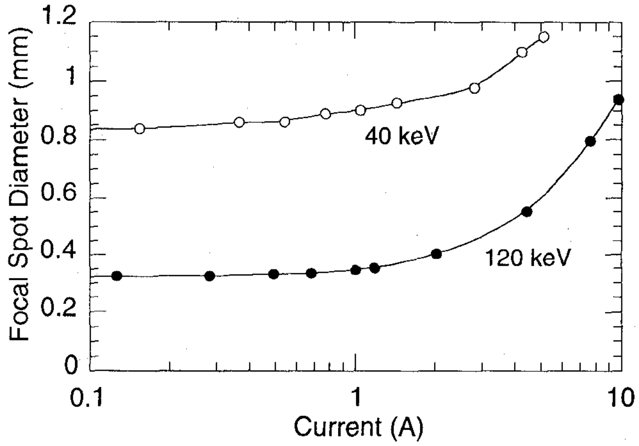

Figure 3: Focal spot diameter versus beam current for electron beam energies of 40 and 120 keV, as computed using EGUN. Simulations assumed an initially parallel beam of radius 5.6 mm focused by a solenoidal magnetic lens with an inner radius of 10 mm and a current density of 150 A•turns/cm^2.

B. Cathode Grid

A fine wire mesh grid located a short distance in front of the metal cathode provides a means of controlling the beam current. By pulsing the grid voltage appropriately, it is possible to vary the current coming off of the cathode such that it swings between a peak current level and zero. A cathode grid will intercept around 10% of the current emanating from the cathode, with increasingly higher intercept percentages the more positive the grid is driven [14].

For a 1 cm^2 cathode with a 1 A peak current, a grid cutoff voltage near –400 V and a peak drive voltage near +400 V are effective, as is the 1 mm cathode-to-grid spacing used in [14]. By driving the grid with a high-frequency voltage pulser, 5 ns electron pulse widths are commonly achieved. The capacitive, nonlinear nature of the grid impedance, however, makes driving the grid with high-frequency pulses tricky and necessitates careful design of the pulser electronics [6].

C. Sweeping and Chopping the Electron Beam

Sweeping the pulsed electron beam past the aperture is accomplished by rapidly varying a bipolar voltage on one deflection plate while the second plate is kept grounded. This process is summarized in Figure 4.

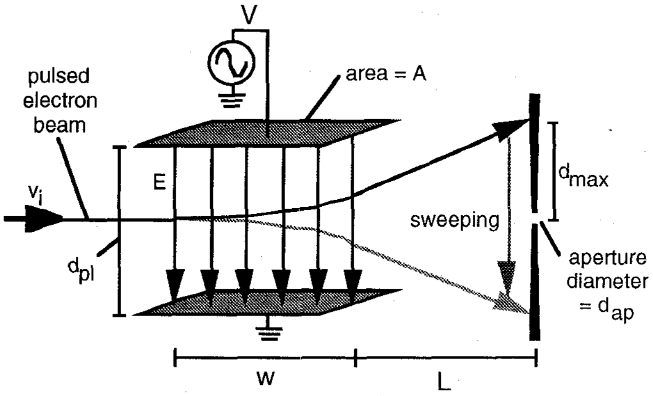

Figure 4: The pulsed electron beam is swept past the aperture by deflection plates, thereby reducing the time duration of the post-aperture electron pulses.

To first order, the time required to sweep the electron beam past an aperture of size d_{ap} (i.e., the beam travels a vertical distance equal to d_{ap}) is:

$$\text{electron pulse width} = \frac{d_{ap} \cdot d_{pl} \cdot m_e \cdot v_i^2}{\frac{dV}{dt} \cdot w \cdot \left(\frac{w}{2} + L\right) \cdot q_e} \qquad (1)$$

where d_{ap} is the aperture diameter, d_{pl} is the distance between the deflection plates, v_i is the beam velocity, dV/dt is the maximum rate of voltage switching, w is the length of the deflection plates, and L is the plates-to-aperture distance.

To minimize the pulse width it is desirable to make the distance between the plates (d_{pl}) small but their length (w) long. However, the constraint of not allowing the deflection plates to intercept the beam, even at maximum deflection, limits these values. Increasing the plates-to-aperture distance (L) is also attractive, but L is limited in that the farther the beam travels before being brought to a focus, the greater the resulting focal spot diameter. This then leaves the aperture diameter (d_{ap}) and the deflection plate sweeping rate (dV/dt) to be minimized and maximized, respectively. The former is limited by lens aberrations and space charge repulsion, while the latter is limited by voltage switching technology.

With attention to these effects, values of d_{ap} = 0.32 mm, d_{pl} = 35 mm, w = 100 mm, and L = 178 mm were used in the final instrument design. For this geometry and 120 keV electrons (i.e., relativistic velocity of v_i = 0.587c), the dV/dt required to achieve a post-aperture electron pulse width of

10 ps is $8.6 \cdot 10^{12}$ V/s. Because there will be some spreading (in time) of the post-aperture electron pulses during their conversion to x-rays, a slightly faster sweep rate is desirable.

A deflection plate sweep speed of about 10^{13} V/s can be achieved with a power triode and related circuitry [15]. At a modulation amplitude of 16 kV and a frequency of 100 MHz, the maximum dV/dt values will meet this goal. An estimated peak current of 33 A is required to drive the deflection plates at this frequency and amplitude. There are suitable commercial power triodes that meet these specifications [7].

D. Anode Angle

The electron beam is swept by the deflection plates such that, once near the aperture, it traverses a distance equal to the aperture diameter in about 10 ps. At this point the electron beam has been focused to a spot with a diameter equal to the size of the aperture, so electrons will actually pass through the aperture for a period of about 20 ps. The two-dimensional shape of the electron pulse emerging from the aperture will approximately be a parallelogram, with the vertical height equal to the aperture size (0.32 mm) and the length of each horizontal line equal to the distance that the electrons travel in 10 ps (1.76 mm at 120 keV). The process of forming an electron pulse is summarized in Figure 5.

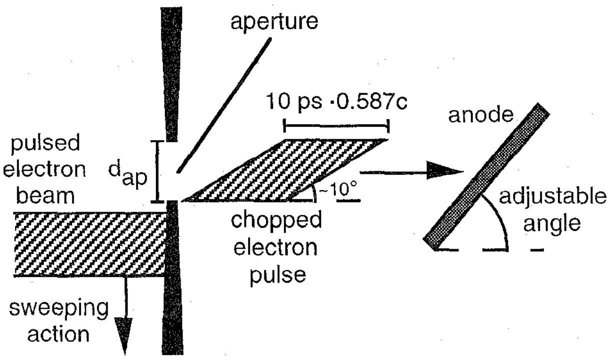

Figure 5: Formation of a post-aperture electron pulse via beam chopping (always done during a sweep in the direction opposite the direction x-rays leave the anode). The resulting pulse will initially have a parallelogram-type shape—the dimensions of which depend on the accelerating voltage and the aperture diameter—before being refocused onto the anode. The anode angle should be adjusted to minimize the electron impact time.

Electron pulses emerging from the aperture will initially demonstrate an angle of about 10° from the horizontal. If the anode is at this same angle, the electrons in the leading edge of the pulse will all strike the anode simultaneously, yielding an x-ray pulse width of about 10 ps. The anode angle should thus be made easily adjustable so that it can be tuned for minimum x-ray pulse width. A quenched, high-speed fluorescent compound can be used to observe the x-ray pulse width while this adjustment is made.

E. X-ray Spectrum

The x-ray spectrum that will be delivered to scintillation samples was simulated using TUBDET [16], the results of which are shown in Figure 6. An anode angle of 10° from the horizontal was assumed, but even large changes in this angle did not significantly affect the spectrum.

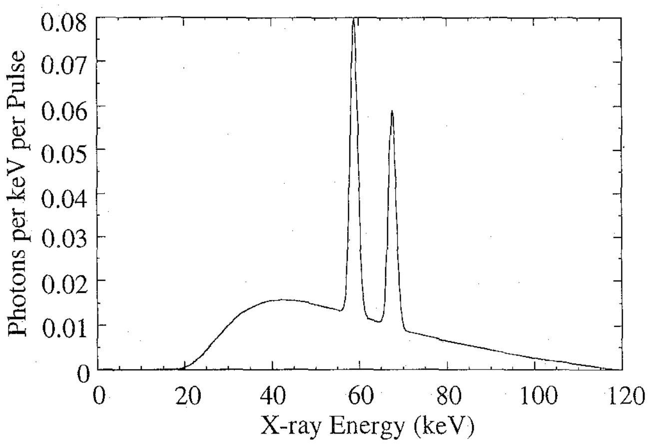

Figure 6: X-ray spectrum delivered to scintillation samples by the pulsed x-ray source, as computed using TUBDET. Pulse widths of 10 ps are assumed, and filtering through both a 0.5 mm Be exit window and a 5 mm Al filter are included. The spectrum assumes a detector energy resolution of 2 keV.

F. X-ray Pulse Width Time Resolution

Another factor not yet considered is time-of-flight across the anode focal spot. X-rays generated from the uppermost electron-anode impacts will have less distance to travel to reach the sample than will those generated from the lowermost impacts, spreading out the x-ray pulse in time. Assuming the maximum deleterious effect, the x-ray pulse width is:

$$\text{x} - \text{ray width} = \text{electron width} + \frac{\text{spot diameter}}{\text{c}} \qquad (2)$$

Hence an anode spot diameter of 0.45 mm could spread the resulting x-ray pulses out over an additional 1.5 ps.

The EGUN simulation results for the entire instrument (Figure 2) allow for a reasonable estimate of the resulting x-ray pulse width. With a maximum deflection plate dV/dt of 10^{13} V/s, the post-aperture electron pulse width calculated with equation 1 is 8.6 ps. Equation 2 yields an x-ray pulse width of 10.1 ps, very close to the desired time resolution.

G. Accelerating Electrons Earlier Versus Later

The electron pulses can either be accelerated through 120 kV immediately (in the electron gun) or they can initially be accelerated through a smaller voltage (e.g., 40 kV) and then through the remaining potential (e.g., 80 kV) in the anode compartment after beam chopping has occurred. Faster moving electrons are easier to focus but harder to sweep, so it is not immediately clear which configuration is best.

Figure 7 displays the estimated x-ray pulse widths over a range of beam currents for first stage acceleration voltages of 40 and 120 kV. These curves use the EGUN data in Figure 3, as well as equations 1 and 2. At 1 A the curves demonstrate better x-ray time resolution with an immediate accelerating voltage of 120 kV, making that the configuration of choice.

Since the data in Figure 7 represent a general solenoidal focusing system (i.e., a simple cylinder) rather than the precise geometry of the x-ray source design, the estimated x-ray pulse

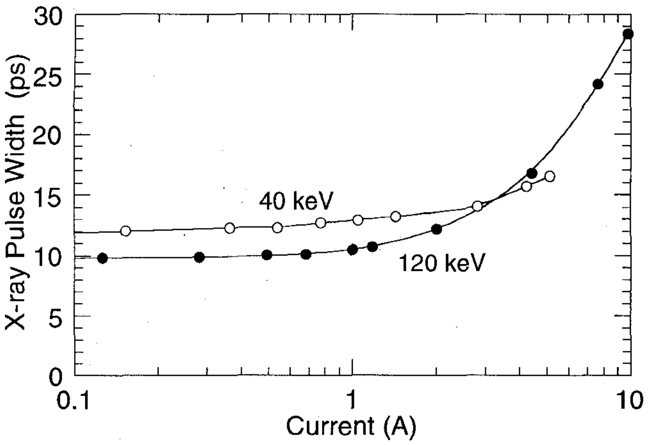

Figure 7: Estimated x-ray pulse width versus current for first stage electron energies of 40 and 120 keV. For a current of 1 A, the estimated resolution is 12.9 ps at 40 keV and 10.7 ps at 120 keV.

width of 10.7 ps for a 1 A, 120 keV beam is not as accurate as the 10.1 ps estimate based on the simulations in Figure 2. The two values are, however, in good agreement.

H. Synchronization of the Grid and Deflection Plates

The pulsing of the cathode grid, which leads to the generation of electron pulses, and the deflection plate zero-crossings, during which the electron beam is aligned with the aperture, must be carefully synchronized. The deflection plates should sweep the beam such that each 5 ns wide electron pulse is aligned with the aperture during its peak current.

Since the deflection plates are modulated with a sinusoidal signal, a zero-crossing detector will provide a reliable measure of when the next few positive-to-negative zero-crossings will occur (e.g., every 10 ns thereafter at 100 MHz modulation). This can then serve as a trigger for the release of an electron pulse from the cathode/grid assembly. An adjustable delay element can be used to fine-tune the system so that the peak pulse current level can be best aligned with the deflection plate zero-crossings. This adjustment can be optimized by observing the x-rays with a scintillator and adjusting the delay until the strongest x-ray pulses are obtained.

IV. CONCLUSIONS

We have presented a conceptual design for a table-top device capable of producing 10 ps pulses of x-rays for ultra-fast fluorescence measurements. In addition to the very short timing resolution, the instrument provides 1 A peak anode current, 100 kHz repetition rate, and 120 keV peak x-ray energy. Each of these features is attractive for characterizing the fluorescent lifetimes and spectra of scintillators, and measuring scintillation responses is thus significantly easier and faster. The very narrow x-ray pulse width is achieved by focusing the pulsed electron beam to a 0.32 mm diameter spot and using deflection plates undergoing a peak dV/dt of 10^{13} V/s to sweep the beam past an aperture. In order to achieve the shortest width and greatest intensity x-ray pulses, both the anode angle and the delay element (in the deflection plate-cathode grid synchronization circuitry), respectively, should be fine-tuned once the instrument is built. The cost of the pulsed x-ray source is estimated at about $200,000 (U.S.).

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