DOE/NV/25945--013
DOE/NV/11718--1251

Microprocessor-controlled, wide-range streak camera

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ABSTRACT

Bechtel Nevada/NSTec recently announced deployment of their fifth generation streak camera. This camera incorporates many advanced features beyond those currently available for streak cameras. The arc-resistant driver includes a trigger lockout mechanism, actively monitors input trigger levels, and incorporates a high-voltage fault interrupter for user safety and tube protection. The camera is completely modular and may deflect over a variable full-sweep time of 15 nanoseconds to 500 microseconds. The camera design is compatible with both large- and small-format commercial tubes from several vendors. The embedded microprocessor offers Ethernet connectivity, and XML [extensible markup language]-based configuration management with non-volatile parameter storage using flash-based storage media. The camera's user interface is platform-independent (Microsoft Windows, Unix, Linux, Macintosh OSX) and is accessible using an AJAX [asynchronous Javascript and XML]-equipped modem browser, such as Internet Explorer 6, Firefox, or Safari. User interface operation requires no installation of client software or browser plug-in technology. Automation software can also access the camera configuration and control using HTTP [hypertext transfer protocol]. The software architecture supports multiple-simultaneous clients, multiple cameras, and multiple module access with a standard browser. The entire user interface can be customized.

Keywords: streak camera, streak tube, XML process control, AJAX

1. BACKGROUND

Streak cameras measure ultra-fast light phenomena with respect to time and position by sweeping a row of optical inputs across a phosphor screen. Measured light is effectively collected as it passes through a slit and onto the photocathode as shown in Figure 1. The incident light on the photocathode is converted into electrons. The number of electrons produced is directly proportional to the intensity of the light source. The resulting electrons pass through a pair of deflection plates that skew their path onto a phosphor screen[1]. The electrons are propelled onto the phosphor by negatively charging the photocathode to several kilovolts relative to the phosphor screen. The electrons bombard the phosphor and produce an image proportional to the spatial resolution and intensity of the light source. Streak tubes image in both spatial (horizontal) and temporal (vertical) dimensions. Spatial resolution refers to the light imaged horizontally relative to the position of the input light at the slit, while temporal resolution refers to the vertical sweep of the input light along the phosphor screen with power applied to the deflection plates.

The streak camera uses an electrostatic image tube with deflection plates to sweep the input signal. The tube images electrons onto the phosphor screen with an electrostatic lens. The lens provides a drift region where deflection of the electrons occurs. The deflection field must develop such that the potential in the drift region is maintained close to 0 V. To this end, the deflection must be balanced, that is, there must be an electric field perpendicular to the beam such that the potential on the vertical axis is zero. This is achieved by applying equal but opposite potentials to a pair of deflection plates across the electron beam path. A ramped voltage is applied to each plate. If a particular electric field is maintained across these plates, then the beam is deflected to a certain position on the screen. By ramping the field, the beam is swept. The ramp speed is controlled to achieve as linear a sweep rate as possible. By changing the ramp rate, the sweep speed is controllable. Streak images are typically recorded by a CCD [charge-coupled device] camera directly coupled to the streak tube through a fiber-optic window. The light persistence on the photocathode allows a CCD camera to record the light.

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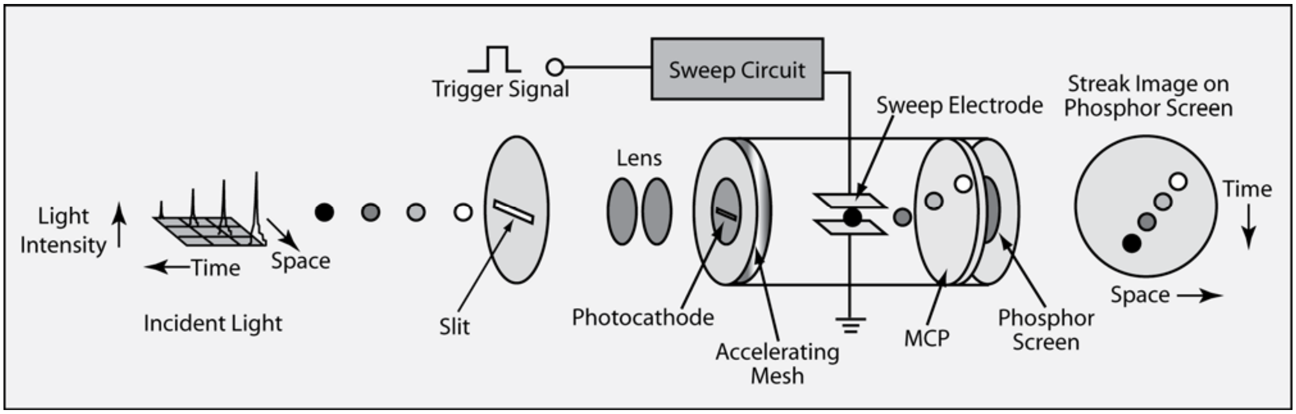


Figure 1. Basic Streak Camera Operation. The measured light passes through a slit onto the photocathode of the streak tube producing electrons. The electrons pass through a pair of deflection electrodes and strike a phosphor screen to produce the streak image. A microchannel plate (MCP) may be used to amplify the light intensity[2].

Large- and small-format tubes have input areas 35 mm and 18 mm wide, respectively, and output diameters of 50 mm or 25 mm, respectively. Streak systems provide greater than 18 lp/mm [line pairs per millimeter] spatial resolution and a radiant gain of better than 10. Quantum efficiency percentages approach 20 for most commercial streak tubes. Input signals may be lens-coupled or directly fiber-optically coupled through a linear fiber array. Streak images are typically recorded by a CCD camera directly coupled to the streak tube through a fiber-optic window. Gate turn-on delay is typically 40 to 100 ns, depending on the tube. The sweep voltage is generally sufficient for parking the end of the sweep off-screen to minimize phosphor afterglow.

2. INTRODUCTION

The Generation V streak camera system consists of electrical and optical timing sources, high-voltage control electronics, and a CCD camera arranged as shown in Figure 2. Two camera triggers (Figure 3), one each for the deflection and gate modules, drive the system. The control, gate, and deflection modules comprise the camera head subsystem. The gate module shutters the camera from 100 ns to 500 μs in 10-ns steps. The deflection module generates the ramps necessary to record the light evolution; the duration of the ramps determines the length of recording from 20 ns to 500 μs for a large-format streak tube. The control module includes a digital-to-analog converter (DAC) and a commercial-off-the-shelf (COTS) on-board microprocessor as well as the custom electronics that interface between the high-voltage optical controls and the microprocessor. The 630-nm optical fiducial generators function as a separate subsystem and are configurable as either impulse or comb generators to cross-time the image recording. Single or multiple generators may be used in any experimental system configuration. Each subsystem operates independently using an embedded single-board computer (SBC) as an interface between the high-speed control electronics and the camera operator. An operator can configure and

Figure 2. The Generation V Camera. The camera has few hardware controls or indicators and requires an Ethernet communication link and a wall-mounted power supply.

operate each subsystem through a unified graphical user interface (GUI) running in a standard Web browser. Automation systems can also configure and operate all aspects of camera operation using HTTP [hypertext transfer protocal] and XML [extensible markup language] configuration files.

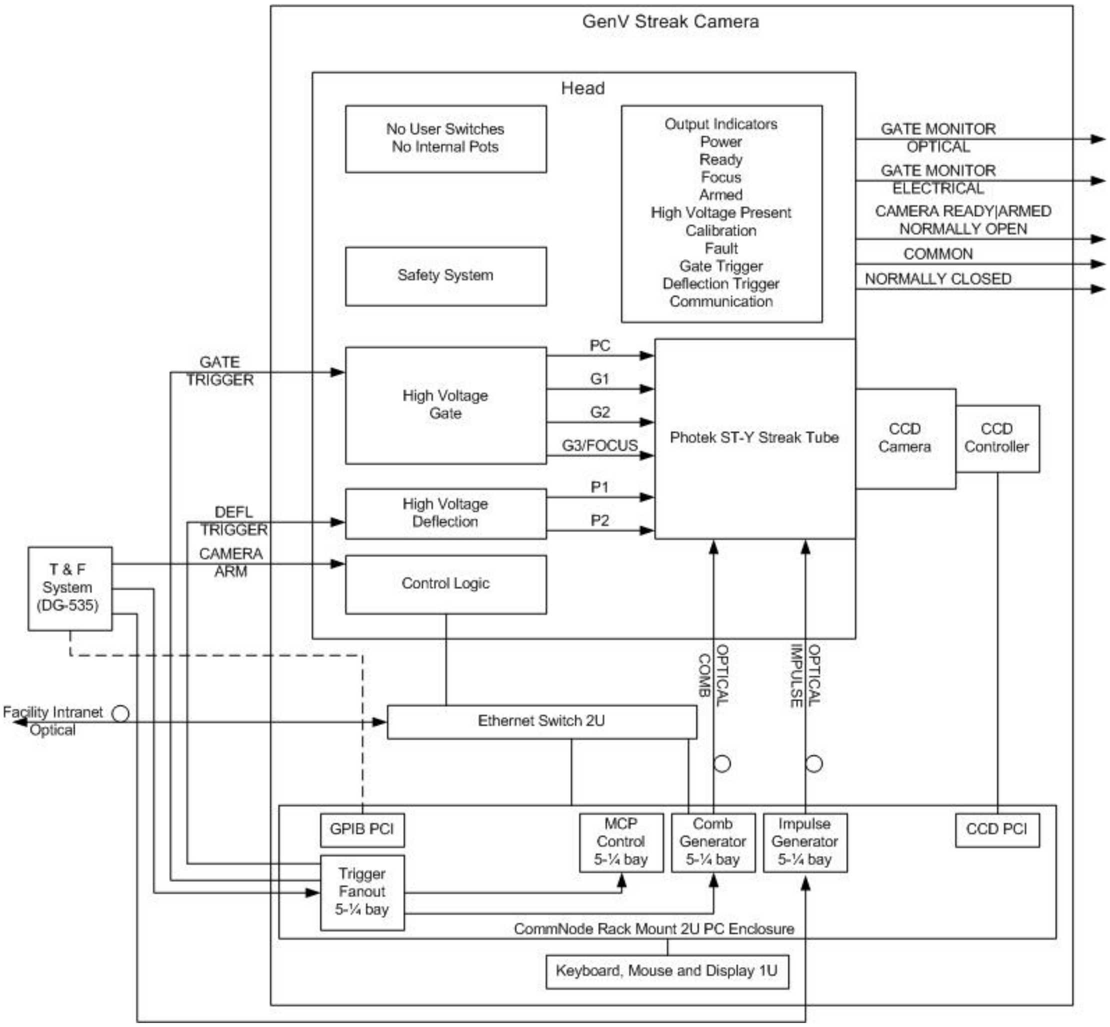


Figure 3. Streak Camera Block Diagram. The camera is comprised of several subsystems: the camera head, fiducial generators, and a communication chassis.

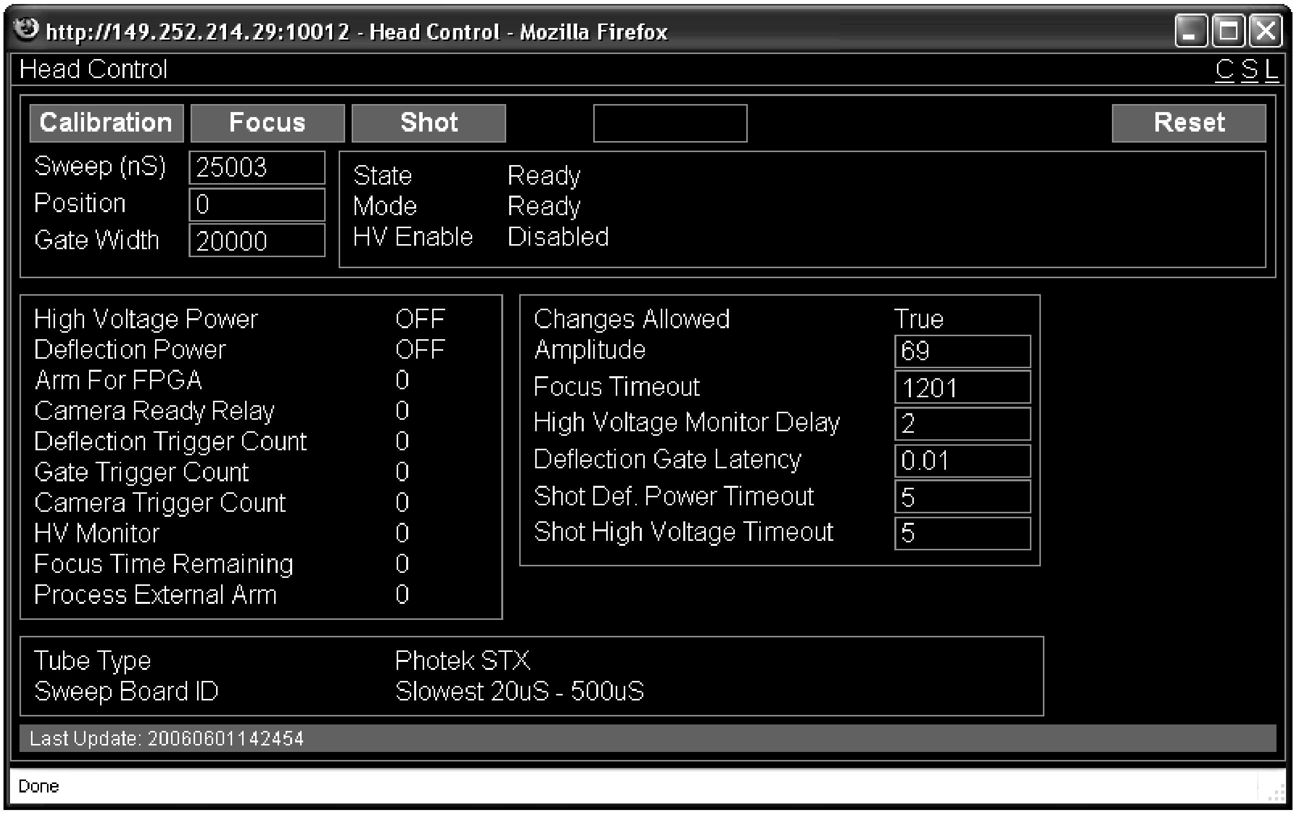
3. CAMERA OPERATION

Experiments requiring the Generation V streak camera have a wide range of system requirements. First, these experiments are quite often executed only once, since repetition is costly or impossible. Therefore, the system must be highly reliable. Second, the Generation V streak camera system is used by experimenters who regularly reconfigure subsystem components. For example, one experiment may utilize a single optical timing source with no CCD image capture capability while another system may require multiple optical sources, electrical timing control, and CCD image capture. The Generation V supports all possible subsystem component configurations with minimal effort. The system also simultaneously supports the following ‘use cases’: single user/single camera, single user/multiple cameras, multiple users/multiple cameras, desktop operation, facility integration, multi-level user access control, and multi-platform user interface support. System configuration and operation control communications use standard non-proprietary HTTP. Configuration files at the system and subsystem level are human and machine-readable XML files.

To initiate camera operation, the user provides two BNC 50-ohm triggers, one for the gate and one for the deflection modules. The gate turn-on, which is delayed 150 ns, may be pretriggerred relative to the deflection trigger for faster sweeps. The triggers are locked-out in hardware to prevent double-triggering the image. The trigger receipt is recorded and available in the GUI. The software will allow another trigger when the camera is again armed. The camera will fault when a high-voltage arc is detected or when both triggers are not received regardless of the mode of operation. The fault conditions inform the operator and allow resumption of camera operation when acknowledged.

The camera has three modes of operation: Calibration, Shot, and Focus. The Calibration mode, intended for setting up the camera and adjusting experimental parameters dynamically, is a swept image recording that allows retriggering of the camera for up to two shots per second. The camera is returned to an armed state after every trigger. The Shot mode, intended for data collection, allows a single event to be triggered and recorded. In this mode experimental settings may not be adjusted. After the shot, the camera powers off and after a user-specified amount of time the entire camera turns off. The Focus mode allows static imaging by disabling the deflection power. Static images are often used to align optical components and experimental arrangements prior to their execution.

The camera head GUI, shown in Figure 4, allows the user to change the sweep time duration, the position on the phosphor where start-of-sweep begins, and the gate opening time. Modes of operation are chosen by clicking the appropriate button. System electronics detect and display the camera's tube model and the sweep ranges on the screen. Additionally, the user may vary the ramp amplitude and set the amount of time that the focus mode stays enabled. Focus mode is potentially dangerous when great amounts of light may be imaged through the tube onto delicate tube optics. An image may be burned onto the phosphor or material from the photocathode may be blown from the glass surface. Light intensities should always be monitored, especially in focus mode.



Sweep (nS)	25003
Position	0
Gate Width	20000

State	Ready
Mode	Ready
HV Enable	Disabled

High Voltage Power	OFF
Deflection Power	OFF
Arm For FPGA	0
Camera Ready Relay	0
Deflection Trigger Count	0
Gate Trigger Count	0
Camera Trigger Count	0
HV Monitor	0
Focus Time Remaining	0
Process External Arm	0

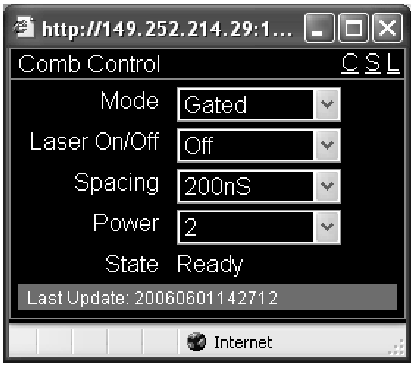
Changes Allowed	True
Amplitude	69
Focus Timeout	1201
High Voltage Monitor Delay	2
Deflection Gate Latency	0.01
Shot Def. Power Timeout	5
Shot High Voltage Timeout	5

Tube Type	Photek STX
Sweep Board ID	Slowest 20uS - 500uS

Last Update: 20060601142454

Figure 4. Camera Head GUI. Sweep speed, position, and gate width are the settings most commonly adjusted. Changes may also be made to amplitude and several timeouts are also allowed. The tube and boards configured into the system are reported to the user.

Optical generators are included in the camera arrangement. The comb/impulse generator may function as either a comb fiducial generator or as a single-event impulse generator. The unit provides an optical output at 650 nm through an ST connector. The 5-mW output is coupled through a fiber array onto the streak tube surface. The light may be fed into a single fiber or split into multiple optical signals. As an impulse generator, the unit produces a single pulse less than 200 ps long. The comb generator produces 100 light pulses at intervals that are configurable by the user. Optical pulse periods of 10, 20, 50, 100, 200, and 500 ns, and 1, 2, 5, 10, 20, and 50 μs are available. The output rise time is less than 2% of the spacing and the jitter is less than 200 ps. A screenshot of the GUI for the comb generator is shown in Figure 5.



Mode: Gated
Laser On/Off: Off
Spacing: 200nS
Power: 2
State: Ready
Last Update: 20060601142712

Figure 5. Comb/Impulse GUI. The mode spacing and power output are user-adjustable.

The unit's three modes of operation are gated, continuous, or impulse. Gated and continuous modes produce time marks, or combs. Continuous operation will produce continuous pulses without receipt of any trigger. The gated operation produces 100 pulses when triggered. The user can control laser output power intensity over a range of 2 to 20 mW in 25-step resolution. Multiple devices may be configured onto a single Web page and connections to all allowable devices can be made through any user-supplied graphic. As an example, the interface for two streak cameras is shown in Figure 6. A system overview provides the basis for the Web page and the blocks connect the subsystem GUIs shown already with a mouse click. Active buttons can be added for *any* experimental arrangement.

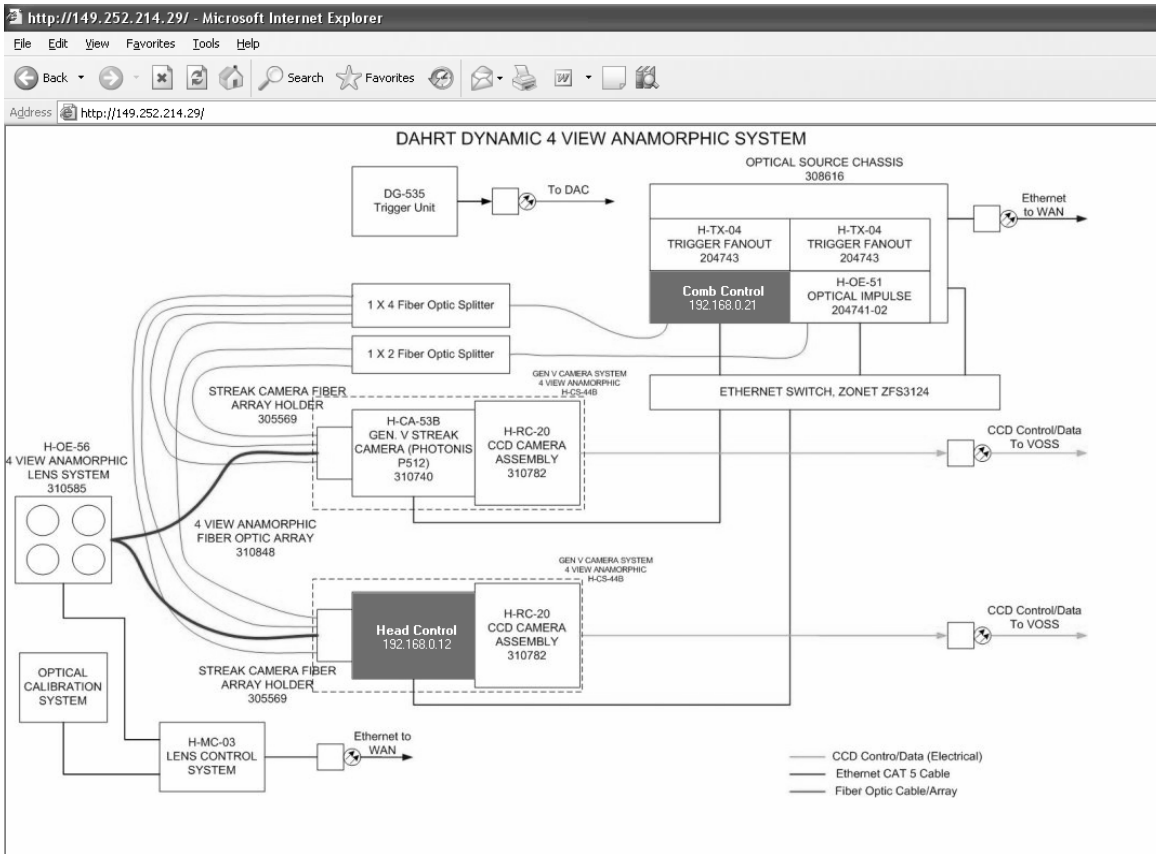


Figure 6. System Configuration Example. Two cameras are fully controllable from the system user interface. Fiducial generators are also connected in this manner.

4. STREAK CAMERA CIRCUITRY

4.1 Deflection Circuit

The streak camera deflection circuit produces variable ramps based on the inputs received from the DAC. These ramps dictate the time duration of the camera recording. DAC lines vary amplitude, slope, and position of the ramps. The slope varies the time required for the ramp to shift 1000 V, while the position controls the DC offest up to 1000 V. The amplitude varies the entire voltage shift of the ramps up to approximately 1400 V. The ramps are created by a double-ended stack of high-voltage metal-oxide semiconductor field-effect transistor (MOSFETs), a technology partially developed by R. J. Baker[3,4]. The deflection generation relies on the use of equal capacitors and resistors to divide the voltage across each of the MOSFETs as shown in Figure 7.

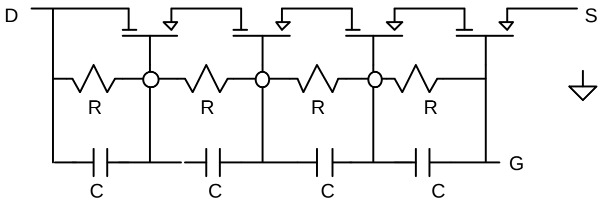


Figure 7. Deflection Ramp Generation. Parallel resistors and capacitors allow for voltage division over 400-V MOSFETs.

This method can produce 2000-V linear ramps with 400-V MOSFETs. This design requires the use of empirically selected series gate resistors to stop the MOSFETs from oscillating at frequencies between 100–800 MHz. There are also boundaries on the value of C. The ramp speed, which is determined by how fast the MOSFETs can discharge the capacitors, is limited. The minimum value of C must be large enough so that the charge drawn from it at startup (to charge the gate-source capacitance, the drain-gate capacitance, and output capacitance of the field-effect transistors (FET) will be a small part of its total charge, or else start-up aberrations will be large. It is noted that the absolute upper limit for speed is determined by the ratio of the MOSFET ‘on’ resistance to its parasitic capacitances (gate-source capacitance, drain-gate capacitance). For a given voltage FET, this ratio is almost independent of FET size. The basic MOSFET technology sets the upper limit.

Because a large value of C is required to reduce start-up transients, this circuit does not reach basic limits. R. J. Baker discovered that additional capacitors from the gate of each FET to circuit ground would divide the voltage between the effective gate-source capacitance (Cgs) and the capacitance to ground (Cdg). Difficulty with the capacitor requirements for the circuit led J. S. Rohrer of Bechtel Nevada to reconfigure the circuit as shown in Figure 8, which allows the capacitor to match the FET voltage rating. To generate a ramp with this circuit only requires a power supply, a drain resistor, a source resistor, and a low-impedance gate drive pulse. The Generation V deflection is essentially based on this circuit. Four different printed circuit boards are necessary to achieve the 20-ns to 500-µs range of this camera. The boards are user-replaceable into an external drawer and cover these overlapping ranges: 20–500 ns, 200 ns–5 µs, 2–50 µs, and 20–500 µs.

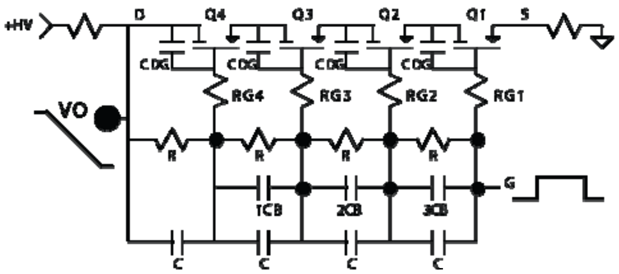


Figure 8. Deflection Generation. R is the divider resistor chosen to have 20 to 100 µA of current. C is the equal-valued divider capacitor, at least one-half of the Cgs of the MOSFETs. Cdg is the external drain-gate capacitance. Capacitors 1CB through 3CB are the so-called transformed R. J. Baker capacitors. CB is equal to Cdg plus the minimum internal Cdg. 2CB is 2 times CB, etc. RG1 thru RG4 are series gate resistors selected for frequency stability.

4.2 Gate Shuttering

The gate module produces optical gate start and stop pulses that shutter the camera. The gate start trigger is initiated by an external trigger to the camera. A primitive field-programmable gate array (FPGA) counter then generates the gate stop pulse at the time delay specified by the user. An image tube, with its photocathode and grid at high negative voltage, may be gated on by translating a pulse for either the photocathode or the first grid to the high-voltage level. In this design, the pulse is sent to the grid so that the photocathode can act as an electrical shield. An avalanche transitor is triggered from an 850-nm vertical-cavity, side-emitting laser driving a silicon photodiode. The small avalanching ON Semiconductor MPS2369A can turn on in 15 ns. Two transistors are used, one for the gate initiation and one for the gate termination, thus, the high-voltage gate electronics are optically isolated from the microprocessor control.

The transistors have to drive a resistive voltage divider across the streak tube. An arc from photocathode to ground may suddenly exceed the gate-to-source ratings of the drive transistors, causing the camera to fail. The protecting Zener diodes cannot react quickly enough to prevent many failures. Capacitive translation requires a signal capacitance and a return capacitance, but a large voltage differential is created when an arc is drawn from only one of these capacitances. That high differential destroys gating electronics and can damage tubes. By ensuring only a single capacitor from the high-voltage electronics to ground, the capacitor voltages fall simultaneously and an arc-based failure is prevented. Capacitors are paralleled with the resistors in the resistive divider to provide similar voltage division during transients. The series-connected capacitors are each valued inversely proportional to the voltage across it. This means that a photocathode arc to ground is survivable when the tube electrode potential falls proportionately and simultaneously.

4.3 Microprocessor Control

Each microprocessor-controlled subsystem functions in a similiar fashion: the SBC provides an interface between the user and the underlying high-speed electronics. The electrical interface, primarily a custom-designed FPGA, uses a standard 8-bit input/output port functionality available on the SBC. Software running on the SBC configures and operates the FPGA. This software runs on top of the Linux operating system as a series of device drivers and application code. The devices are written in C whereas the application code utilizes the scripting languauge Python. The Python application code offers HTTP server functionality and makes use of XML technologies for parameter storage and retrieval. When the user points his browser to an SBC's URL [uniform resource locator], the browser sends an HTTP request to the Python application code. The command is processed and a response is forwarded back to the browser.

Each subsystem user interface relies heavily upon a Microsoft technology developed three years ago called XMLHTTPRequest. Using the browser's Javascript engine, the browser can request small portions of the underlying HTML page, for example, a voltage. The browser can request this voltage, and the Python application accepts the request and returns the voltage value. The browser can then update a small portion of the page containing the voltage value without generating a complete page refresh. The entire browser refresh mechanism, where all parameter and operation values are requested and refreshed, occurs at a programming rate of 1–2 seconds. This browser development approach is called AJAX, or Asynchronous Javascript and XMLHTTPRequest.

5. SYSTEM ARCHITECTURE

The Generation V system architecture archives more reliably by splitting functionality across these subsystem components: comb/impulse generator, head control, and CCD control. Each subsystem contains a COTS SBC running a compact flash-based Linux operating system. These components are network-connected to a private class-C subnet within the Generation V system as in Figure 9. The system chassis primarily acts as a single-point network communication point for external user configuration and control. Each component operates independently from each other and

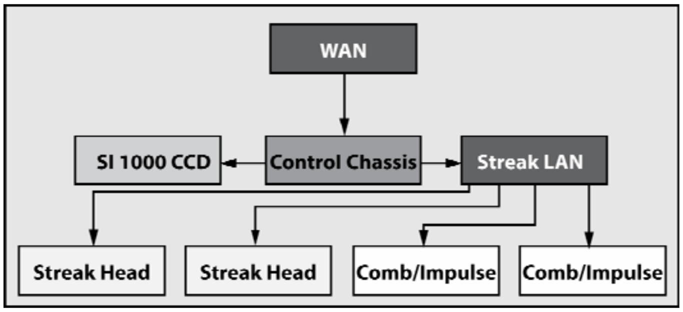


Figure 9. Network Connections. The system components are connected in a private class-C subnet.

functions with or without network communications. Each component can be ‘hot-swapped’ without system functionality loss because the Ethernet switch is the only connection between the components. The SBCs operate from a read-only file system which eliminates the possibility of file system corruption. Component configuration files are stored on a separate journaling file system partition which allows for power downs at anytime without a shutdown procedure. The Linux operating system runs a full version of Debian complete with HTTP server, Secure Shell server, and package management. Each SBC has the capability to self-update while in the field (this feature is not enabled by default).

In recent years, many device manufacturers have moved their existing process control communications to Ethernet from serial or other propriety busses. For maximum backward compatibility, their communication over Ethernet often uses the same protocol that was used by the previous bus structure. This approach provides a migration path for Ethernet but may force the customer or integrator into purchasing propriety communication modules for system integration, an OPC server for example. The Generation V streak camera system does not take this approach; rather, it uses HTTP protocol that ensures there is no barrier to camera acceptance or system integration. The URLs and their corresponding pages are viewable by humans and easily machine parseable. While parsing a form for information is not difficult, with the Generation V, parsing is not necessary. Every Generation V system and subsystem URL accepts an addition parameter, “xmlformat=text”, instructing the device to return a single text value. System configuration settings can be set and queried individually or queried all at once. Each device contains a URL called “_values” that returns a text table such as this:

```
/Comb/Setting/Spacing:5nS
/Comb/Setting/Power:4
/Comb/Setting/Mode:Impulse
/Comb/Setting/LaserOnOff:Off /Comb/Setting/FrontPanelEditTimeout:10
/Comb/Setting/Description:Red Comb
/Comb/Status/State:Ready
/Comb/Status/DriverStatus:Running
```

In addition to providing both human (browser) and machine (text) protocol interfaces, the Generation V system and subsystem components offer configuration operations via XML configuration files. Each component can query for its configuration file. This file can be transferred and saved to the user’s computer or to a facility-wide configuration system. Via the user’s browser or a facility system, each device can also accept a configuration file. This permits storing and restoring all Generation V system parameters. In addition, the system has the capability to internally store configurations. Users, via their browser, can store the current configuration by name. At any time in the future, they can then view a list and restore a previously stored configuration.

The instrumentation world is plagued with a “Windows only” stigma as most manufacturers provide a single solution option addressing the majority marketplace. But the Generation V system is designed to run in any modern browser on any operating system platform. For example, the Generation V has been tested on Internet Explorer 6, Firefox, and Safari running on Windows XP, Windows 2000, Linux, and Mac OSX. The user interface does not rely upon plug-in technology such as Sun Java or Macromedia Flash. The user interface uses AJAX, a mature browser technology that has recently gained acceptance as a desktop development platform. In an AJAX application, the browser can make server requests, process replies, and modify the browser page contents *without* user intervention. This is important because the majority of instrumentation user interfaces simply request, process, and display values. With an AJAX-enabled browser, instrumentation can be brought to all desktops without any additional software installation. Simply put, from *any* browser any operator can connect to a device.

The Generation V user interface requests a device’s values via the ‘_values’ URL explained above using JavaScript. The JavaScript receives the value table, parses it into key value pairs, and then updates the screen elements that are keyed with a new value. Screen refreshes occur once a second without user interaction. During the refresh cycle, the browser is completely responsive. Multiple users can simultaneously access the Generation V system. With each browser making value requests when one user changes a system parameter, all the connected browsers will automatically display that change during their next refresh cycle.

It is possible to control access to the entire system or any subsystem through password protection and to display different types of user interfaces based on a user's technical level. For example, a Generation V subsystem might have an operator interface where all parameters display in a read-only mode, whereas the logged-in technician has read-write interface to the same parameters. This allows for access control to all Generation V parameters. The Generation V file system has ample space for documentation and manufacturing calibration information. The index.html page will have links to this and other important information. With the Generation V, all configuration, operation, and documentation are available using any standard browser.

6. CONCLUSION

The Generation V architecture provides system improvements in camera control, gate circuit resistance to high-voltage arcing, modular removal of deflection circuitry, optical control of the gate circuitry, high voltage failure indicators, trigger fault indicators, separate shot mode that makes all controls automatic, and mechanical swapping of streak tubes. Streak camera control is accomplished via an on-board microprocessor that retains setting information and communicates via an Ethernet connection through a router. Absolutely no software is required to initiate camera operation and any computer may issue command control of the camera within Internet Explorer 6, Firefox, or Safari. The GUI includes user-customizable options. Multiple cameras are easily adapted through an existing browser.

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