

## **OBJECTIVES**

The objectives of this lecture are (1) to understand the basic computer control system architecture utilized by the 3 major OEMs in medical linear accelerators. (2) Understand how mode selection is achieved under computer control for the 3 major OEMs in medical linear accelerators. (3) Understand how beam control is attained via computer control for each of the three major OEMs. (4) Gain insight into how fundamental accelerator design dictates various aspects of computerization of medical linear accelerators. (5) Gain insight into how fundamental accelerator design impacts the design and implementation of IMRT on a particular linear accelerator platform.

## **DISCLAIMER**

Here are presented overviews of the control systems for typical Elekta SL-25, Siemens Primus and Varian CL-21EX/2100C medical linear accelerators. As they are overviews, the intent is not to focus on the details of any specific version of software or model of machine, but to provide insight and understanding consistent with the objectives above. All information presented here was obtained from or derived from either public sources or documentation provided with the systems. No "proprietary" information has been knowingly included or utilized by the author.

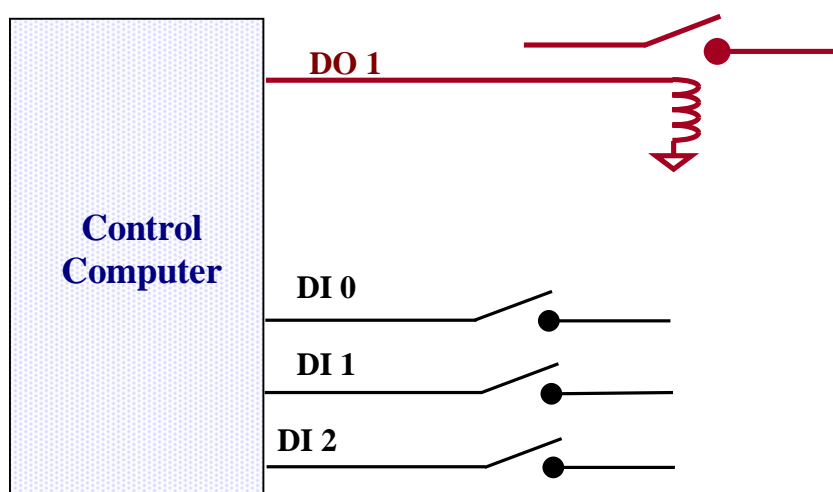
## **HISTORICAL BACKGROUND**

Between 1985 and 1987, six patients were massively overdosed during radiotherapy treatment on AECL Therac 25 linear accelerators. The cause of these incidents is generally considered to be rooted in a lack of hardware-implemented safety functions as well as flaws in the software design and testing process used by AECL. The Therac 25 was a departure from its predecessors, the Therac 6 and Therac 20. On the earlier units, the computer control acted as an overlay upon the already-functional linear accelerator in the form of an operator interface. In the case of the Therac 25, many functional controls and monitors were implemented in software rather than hardware. This absence of hardware-based safety interlocks set the stage for phase errors and race conditions occurring during program execution to allow beam on while beam modifiers such as the target and scanning magnets were not properly placed in the beam path. Allegedly the manufacturer initially denied that this type of malfunction was possible, and when their own engineers and service personnel could not duplicate the problem, they allegedly assured users that the equipment was safe and avoided effort to notify other users of the incidents that had occurred. Malfunctions continued to occur, and ultimately the Therac 25 product was recalled from clinical use.

Anytime a patient injury occurs and there are allegations of machine malfunction, it may fall to the Medical Physicist and/or Radiotherapy Service Engineer to independently determine whether or not an individual treatment machine is safe for use. To make this determination independently requires some understanding of how the machine is controlled.

The remaining medical linear accelerator manufacturers responded to the Therac 25 catastrophe by adopting a design philosophy that incorporates full implementation of controls and monitors or interlock functions in hardware are supplemented by, rather than supplanted by the software. In this paradigm, the computer acts as a parallel or augmentative status monitor and operator interface, rather than as the immediate monitor/controller.

Figures 1 and 2 are a simplified depiction of this paradigm shift. In Figure 1 is a simple representation of the "computer only" approach to control and monitoring. Here three switches, SW0, SW1 and SW2 indicate the position of the flattening filter. The data represented by the filter position is input to the computer via data input lines DI0, DI1 and DI2. When the bit pattern on these input lines matches the coded value for the selected mode of operation, output line DI0 pulls in the high voltage (HV) control relay, allowing HV to be turned on. Here a bad port line or software error that mis-interprets the position of the filter could allow HV voltage to be applied even though the filter is in the incorrect position. In Figure 2, a hardware comparator circuit has been added, as well as 3 output bits from the computer (D1 – D3).



**Figure 1:** Computer control without hardware backup. The control computer enables or disables the HV ON line based on inputs from Filter Position Switches. In the event of software bug or switch failure, the HV could be turned on with a filter out of position.

These 3 output bits represent the expected filter code for the selected mode. If the hardware comparator detects a mismatch between the expected data from the computer and the actual data from the switches, the HW Filter interlock relay opens, preventing the HV enable from occurring without regard to activity on the part of the computer. The output of the hardware comparator circuit is also fed to the computer to facilitate the decoding and display of the interlock condition.

**Figure 2:** Computer control with hardware backup. The control computer enables or disables the HV ON line based on inputs from the Filter Position Switches. A hardware comparator also enables or disables the HV after comparing the expected data on DO 0 – DO2 with the filter switch data. In the event of software bug or switch failure, the HV could not be turned on with a filter out of position.

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## **CONTROL SYSTEMS OVERVIEW -COMMON FEATURES**

Presented here are overviews of the control system architecture and elements of mode and beam control subsystems for each of the three major medical accelerator manufacturers.

Some elements of consideration which are common to all three machine systems:

- Each of the machines is multimode. That is, capable of producing 2 or more photon beams and a number of electron beams. This implies sufficient complexity that accidents of the type experienced with the Therac 25 are possible.
- For interlocks that may affect dosimetry or safety, all have some form of hardware implementation in addition to the software/computer control. Beam on may be prevented through hardware interlocks regardless of the condition of the computer control system.
- All three have some form of "watchdog" timing system which ensures computer events occur within certain time periods (I.e., if an event is "late", it may be due to some malfunction in communications or processing). This typically is implemented with more than one signal and monitoring scheme. Typically this watchdog timer approach is used to trigger a hardware implemented interlock
- Each control system is designed such that the process of operation is divided into specific states, such as "On", "Setup", "Ready", "Beam On", "Normal Terminate", "Abnormal Terminate", etc.
- The control system may only be in one state at a time, and it may only progress from the current state to the next state, or the last state (in some instances).
- The transition from one state to another is monitored by the control system, and deviations from proper transition result in "System" interlocks that may require additional diagnostic or service actions before resumption of use.

## **CONTROL SYSTEMS OVERVIEW** (-In alphabetical order by manufacturer name.)

### **ELEKTA**

#### **DESCRIPTION OF MACHINE**

The Elekta SL-25 is a dual-photon travelling-wave linear accelerator. Up to 9 electron energies may be available. The microwave system is magnetron-based; the electron injector is a diode (non-gridded) type. The bending magnet is a 202.5° slalom arrangement made up of three alternating-direction sectors. Electron flattening is accomplished through dual foil scattering. A dual-channel, segmented ionization chamber is used for dosimetry monitoring.

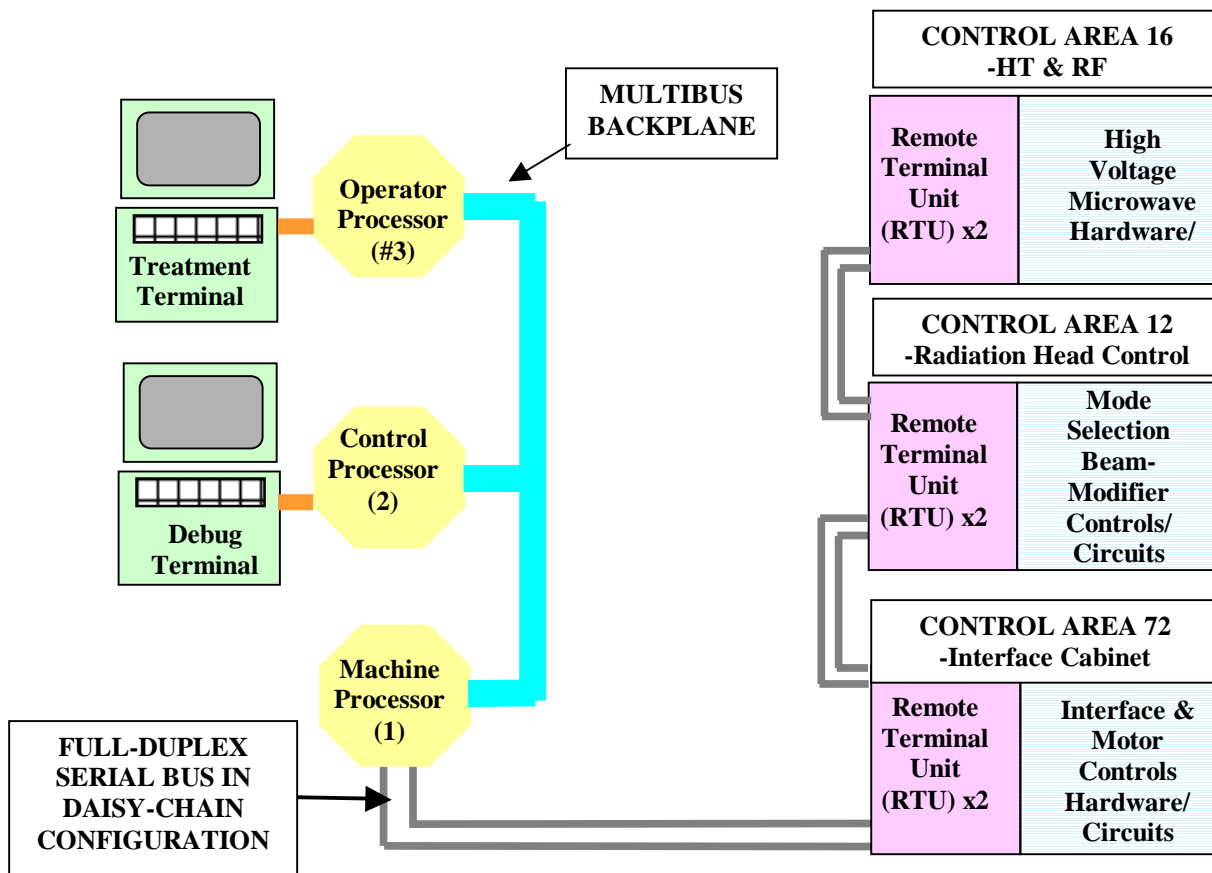
#### **CONTROL SYSTEM ARCHITECTURE**

The Elekta central control system is comprised of three processors and peripherals at the console that reside on an "Intel Multibus 2" bus structure, that in turn communicate with distributed control elements in the linear accelerator via a dual serial communications link. This architecture is illustrated in Figure 3. The console processors and their function are listed in Table 1 below:

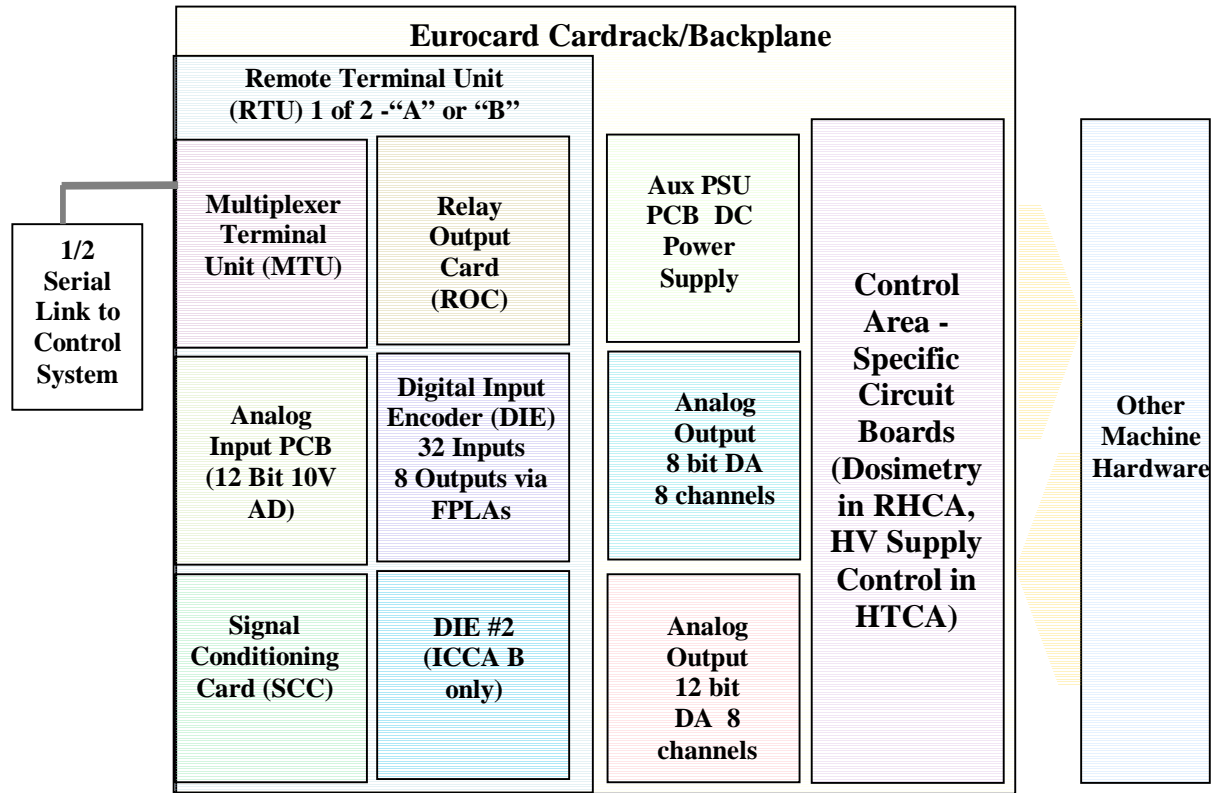
<b>Table 1. Elekta Control System Console Processors</b>		
<b>Processor Name</b>	<b>Type</b>	<b>Function</b>
Machine Processor 1	Intel 8086	Controls serial link between the console and the Control Areas (the remainder of the linac).
Control Processor 2	Intel '486	Controls linac by communicating with the Machine Processor 1. Acts as interface between linac and operator console.
Operator Processor	Intel '486	Controls computer system at console. Functions as interface between user and linac.

The distributed control elements are located in three functional areas of the linear accelerator, referred to as Control Areas. These are connected to the Machine Processor by means of a full-duplex daisy chain serial communications link. The three Control Areas are the Interface Cabinet (ICCA), the Radiation Head (RHCA) and the High Tension and Radio Frequency (HTCA). Each Control Area has two redundant processors called Remote Terminal Units (RTU) whose function is to act as the interface between the various functional circuits in the Control Area and the Machine Processor 1. Each RTU contains a processor, or Multiplexer Terminal Unit (MTU), Analog to Digital (AD), Digital to Analog (DA), and signal conditioning circuitry as well as circuits specific to the function of the Control Area. Hardware logic for controls and interlocks is also implemented within each control area through the use of FPLAs. Hardware interlocks are implemented locally within each Control Area, with status forwarded to the central control system through the serial link.

Logic implemented in the FPLAs controls the two high voltage interlock circuits that pass through each control area. Control Area architecture is illustrated in Figure 4. Status data for the machine are arranged in structures known as Items. Items are numbered from 1 to 799, with each corresponding to some switch, potentiometer or operating parameter of the machine. An Item structure consists of an array of Parts, where each Part describing some aspect of the Item, such as upper and lower limits, current value, scaling factor, or action to be taken in the event a part is out-of-range. In service mode, items can be displayed and manipulated directly via the Debug terminal. The operator interface manipulates Items indirectly in clinical mode through the interface/operating terminal.



**Figure 3:** Overall control system architecture for Elekta SL-25.

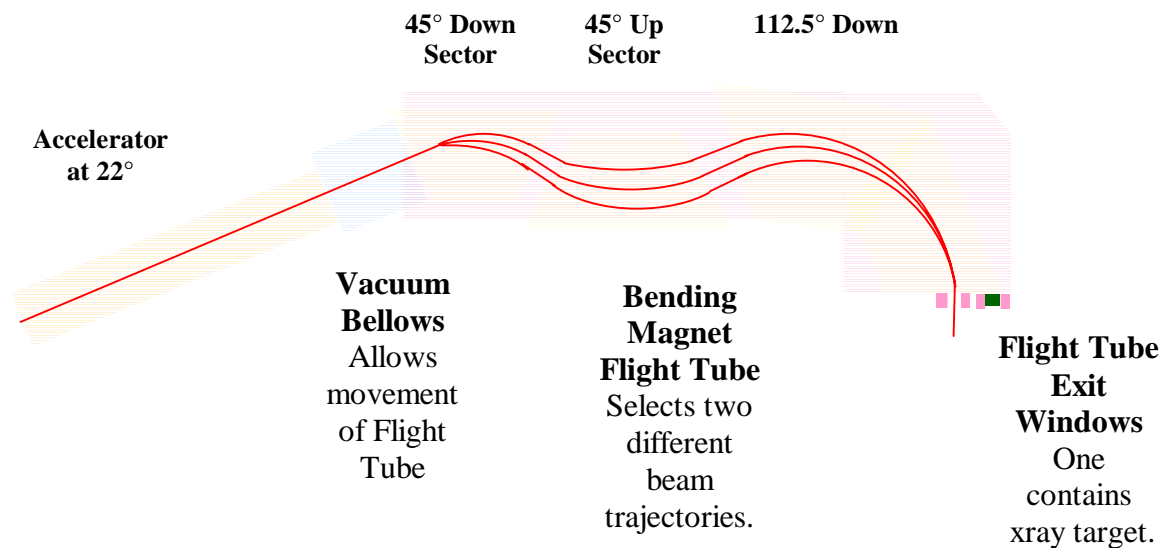


**Figure 4:** Control Area subsystem architecture

## MODE SELECTION

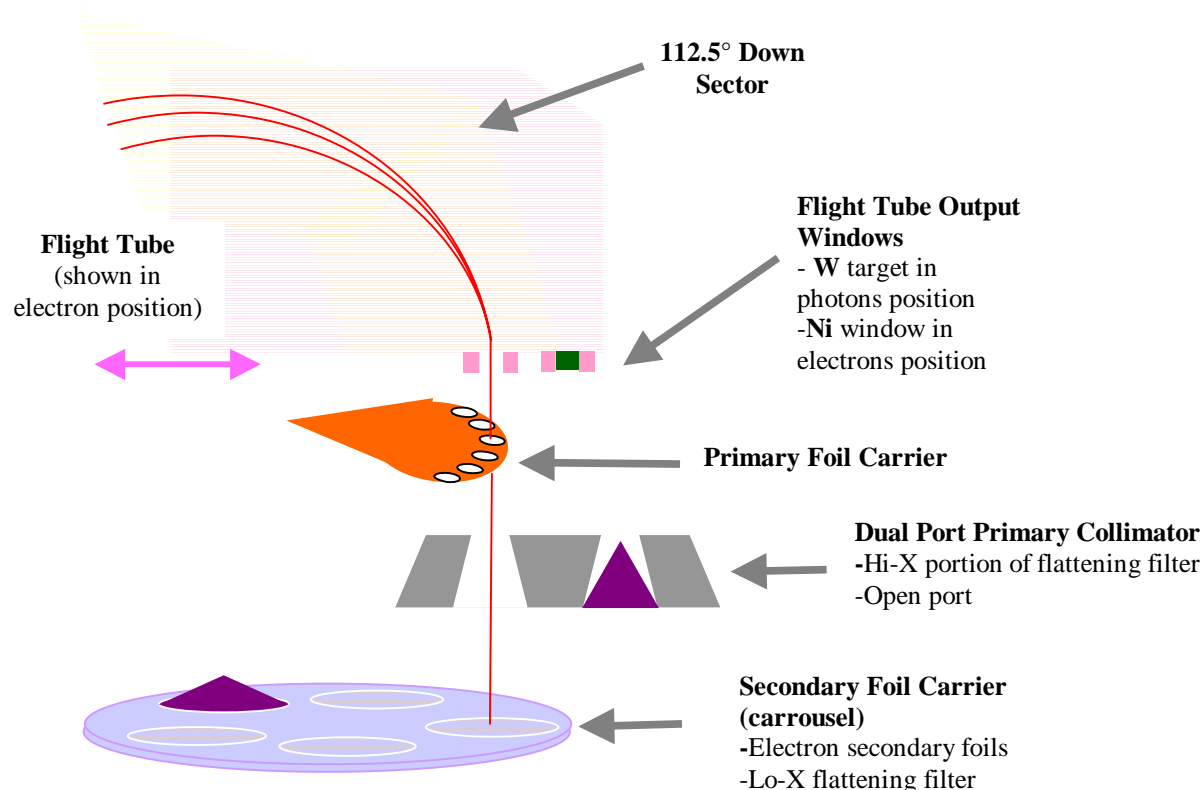
As Elekta uses a travelling-wave accelerating structure, the intrinsic beam energy (the beam energy proximal to the bending magnet) is chiefly a function of the microwave frequency. The microwave power level must be above the threshold necessary to accelerate the injected electron fluence, but otherwise power level does not primarily determine energy spectrum at the exit of the accelerator. The final energy spectrum is selected by a bending magnet system. This bending magnet consists of three alternating sections of 45° down, 45° up, and 112.5° down. The bending magnet is represented in Figure 5. The electron beam exits the accelerator through a vacuum bellows into the bending magnet flight tube, which is mounted between the three the pole pairs of the bending magnet system such that it may be translated along the beam path. The flight chamber has more than one exit window to accommodate multiple exit points afforded by this arrangement, with a tungsten target at the photon position and a thin window for electron mode. The chief advantage of this particular bending magnet system is that it is compact in the vertical aspect, unlike 270° loop magnets. Primary scattering foils are mounted in a pivot array that is rotated into place as needed. A dual-port collimator can be in either of two positions; one for electrons and the "low-X" beam, the other for the "high-X" beam, contains the "high-X" portion of the flattening filter system.

Secondary scattering foils and the "low-X" flattening filter are mounted on a circular carousel that is rotated to the port corresponding to the selected mode. Note that in "high-X" mode both flattening filters are placed in the beam path, and together comprise the "high-X" beam flattener. Details of the beam modifiers in the head are illustrated in Figure 6. The positions of all of the above items are monitored by means of microswitches and potentiometers. The outputs of these sensors are input to FPLA logic in the Control Areas. Should an unexpected switch combination occur during operation, the FPLA logic output disables one or both of the interlock chains to prevent beam on. This data is made available through the Control Area RTU to the Machine Processor via the serial link, and decoded for display at the operator terminal(s). In the event this hardware interlock should fail, the control system will disable a transition to the HV on state by not generating the control command to do so, and will also assert a controller-level interlock to indicate the mismatch between the control system status and hardware status. A similar interlock scheme is used in the other two control areas, in which the HV chain may be disabled via FPLA logic in the Control area RTU.



**Figure 5:** Simplified layout of 202.5° bending magnet system, flight tube, bellows, and dual ports (conceptual).





**Figure 6:** Elekta SL-25 beam modifiers/mode selection items in head of machine (conceptual).

## BEAM CONTROL

In the SL-25, a gun/injector pulse is generated for every HV/microwave pulse. The pulse rate is 200 PPS for a nominal dose rate of 400 MU/minute, or approximately 0.03 MU/pulse. Dose rate is selected by adjusting the HV and Injector pulse repetition frequency (PRF). The dose rate is not “servoed”, or controlled for some specific value, but allowed to vary slightly. Dose rate may increase to the nominal value during “run up” as the magnetron is tuned for the correct frequency. In the case of machines used for IMRT, the magnetron may be equipped with electronic tuning, wherein the tuning plunger is moved by a linear actuation solenoid rather than by the more conventional chain/gear drive. This greatly reduces tuning time, resulting in more instantaneous nominal dose rate at beam on. Beam energy is monitored by comparing the signal on a pair of inplane or radial electrodes in the ionization chamber. If the beam trajectory through the bending magnet system is correct, then so is the energy spectrum. When this occurs, the beam is centered on the ion chamber, and the difference between the electrodes is minimized.

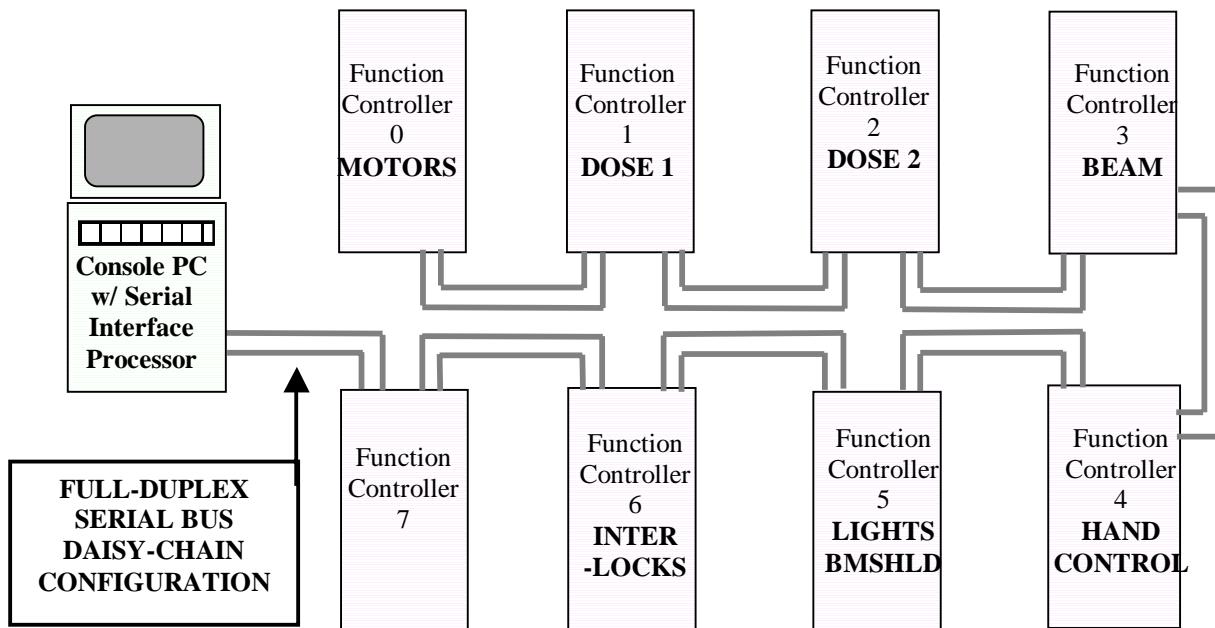
If the energy spectrum is not correct, the trajectory through the bending magnet will result in a deviation at the ion chamber, and a signal difference on the inplane electrodes.

This signal is used to adjust the injector current either up or down, resulting in the electron fluence increasing or decreasing. This adjustment of beam "loading" changes the energy spectrum, and so the trajectory through the bending magnet is altered, and signal difference on the ion chamber sectors is minimized.

## SIEMENS

### DESCRIPTION OF MACHINE

The Siemens PRIMUS series are dual photon standing-wave accelerators. Microwave excitation may be by either magnetron or klystron. Electron injection is by means of a triode (gridded) gun. The bending magnet system is a 270° loop with fixed slits. Dual scattering foils are used for electron field flattening of up to 6 electron beams. The mode motions are accomplished by several mode slides bars that translate to move the correct combination of target, filter and foils into the beam path. Two slide-mounted dual-channel segmented ionization chambers provide dosimetry monitoring; one for photons and one for electrons.



**Figure 7:** Siemens Primus overall control system architecture.

## CONTROL SYSTEM ARCHITECTURE

The overall diagram of the Siemens digital control system is shown in Figure 7. The console computer is an Intel x86-based PC. It is connected as the master Serial I/O Processor (SIP) to the machine via a serial communications link, and acts as the user interface to the machine. Control functions of the system are divided among eight 8051-based Function Controllers (FCs). Assigned tasks for each controller are shown in Table 2. These FCs are connected to the control console and each other via a full-duplex serial daisy chain topography. All of the controllers are interrupted when polled by the master, but only the FC being addressed processes the data block and responds. The response is in the form of an "ack" (acknowledge) bit in the case of no data, or the appropriate data in response to the query. The serial link at each of the FCs is fed through to each of the others and will inhibit communications to all in the event any one of the controllers fails to respond.

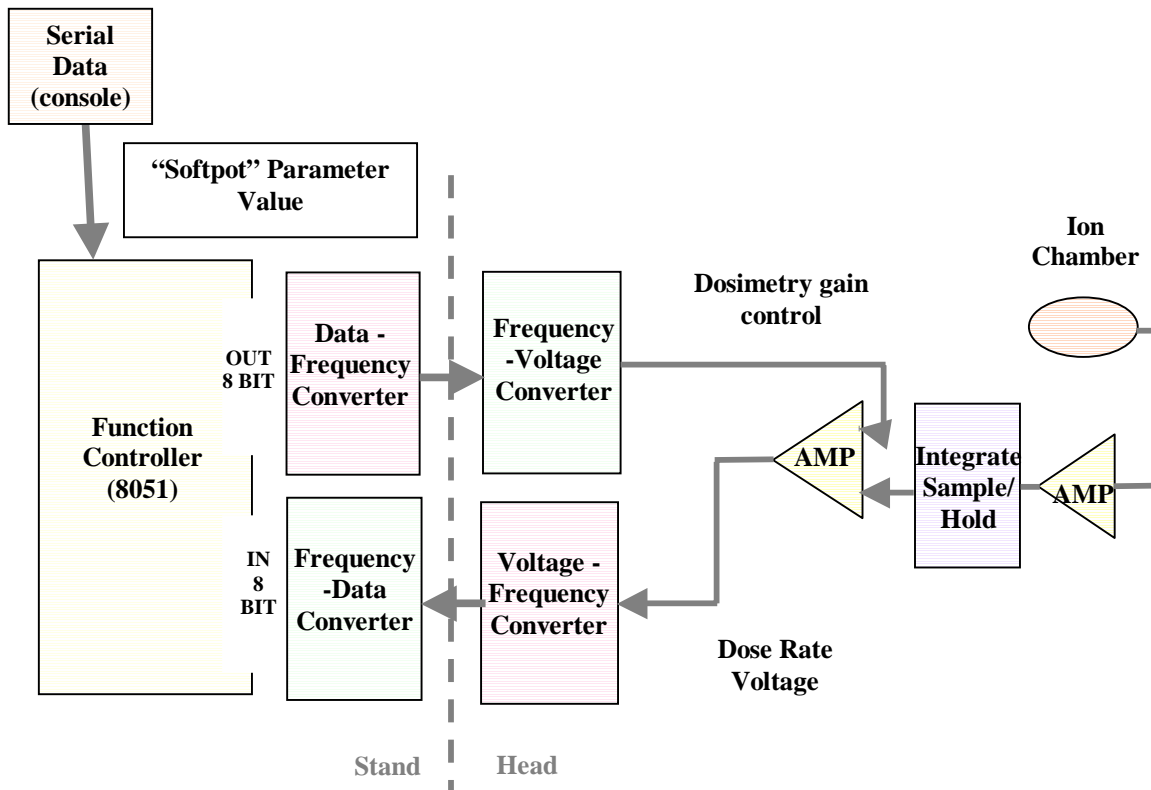
In addition to the serial connections, there are also four control signals lines of interest in terms of the Function Controller operation. These are the T1 "terminate" line and three "Supervisor" enable signals. The three enable signals are fed to function controllers numbers 0-4, 6 and 7; and their status enables or suppresses Rad On, HV On, or Gantry (motion). The condition of the three enable lines is a function of both the Logic Interface PCB and the function controllers themselves. Control and configuration information is sent to the I/O function controller #7 from the console. This data is in turn sent to the Logic Control PCB where it is decoded with respect to current machine status. The result of this decoding determines the proper configuration of the three supervisor lines for the current machine state. In the event of an unexpected configuration of the three enable lines at one of the function controllers, that FC will "time out", and will not send its timing signal to the Watchdog PCB (see below). The operation of these "supervisor" signals enforces the machine state paradigm of proceeding from one state to another in the processing cycle.

<b>Table 2. Siemens Control System Function Controller Assignments</b>		
<b>FC No.</b>	<b>Function</b>	<b>Tasks</b>
0	Motor	Jaws, gantry rotation, collimator rotation.
1	Dosimetry 1	Dose Monitor 1, Odd -numbered chamber segments, Parameter Backup, Pressure1 and Temperature1, Dynamic Steering
2	Dosimetry 2	Dose Monitor 2, Even-numbered chamber segments, Pressure2 and Temperature2, Dose Rate Control Voltage (servo).
3	Beam	Electromagnetic Power Supplies (i.e., bending magnet), Automatic Frequency Control (AFC) Pre-position, AFC Feedback Mode, Open Loop Dose Repetition Rate, Injector Voltage and Current, and Pulse Forming Network (PFN) Control
4	Handcontrol	Hand Control Functions
5	Lights, Beam Shield	Extend/retract Beam Shield, Field Light, Backpointer, Range Light, Room Light Control.
6	HW Interlocks	Hardware Interlock PC Boards
7	Input/Output	I/O Relay PCB, Motor Enables, Accessories, Trigger Delay Values, Target, Filter Ion Chamber Positioning.

The T1 or "terminate" line is controlled by the Watchdog PCB, which takes input of a timer signal from each of the function controllers at 20 mSec intervals. In the event that one of the timing signals is late more than 100 mSec, the Watchdog PCB will enable the T1 line to all function controllers, suppressing their transition to the HV On state and/or forcing transition out of the HV On state. The T1 line is also connected to the hardware interlock system via the Interlock PCBs, and so the T1 activates a hardware suppression of HV as well.

The Function Controllers are connected to the Machine Control circuits through Interface PC Boards, which encode and decode digital and analog values to and from frequency data. Differential and single-ended frequency encoding of voltages and digital data is used for noise immunity. The Machine Control Circuits consist of the analog and digital control circuitry needed to operate and monitor the linear accelerator, such as the dosimetry, mode selection or motor control circuits.

Interlocks are implemented via Interlock PCBs, connected between the hardware and interface electronics. Safety and dosimetry functions are interlocked via hardware locally as well as through software, and interlocks may be asserted either via local hardware connected to the Interlock PCBs or by means of the function controller connected to the Interlock PCBs through interface electronics.

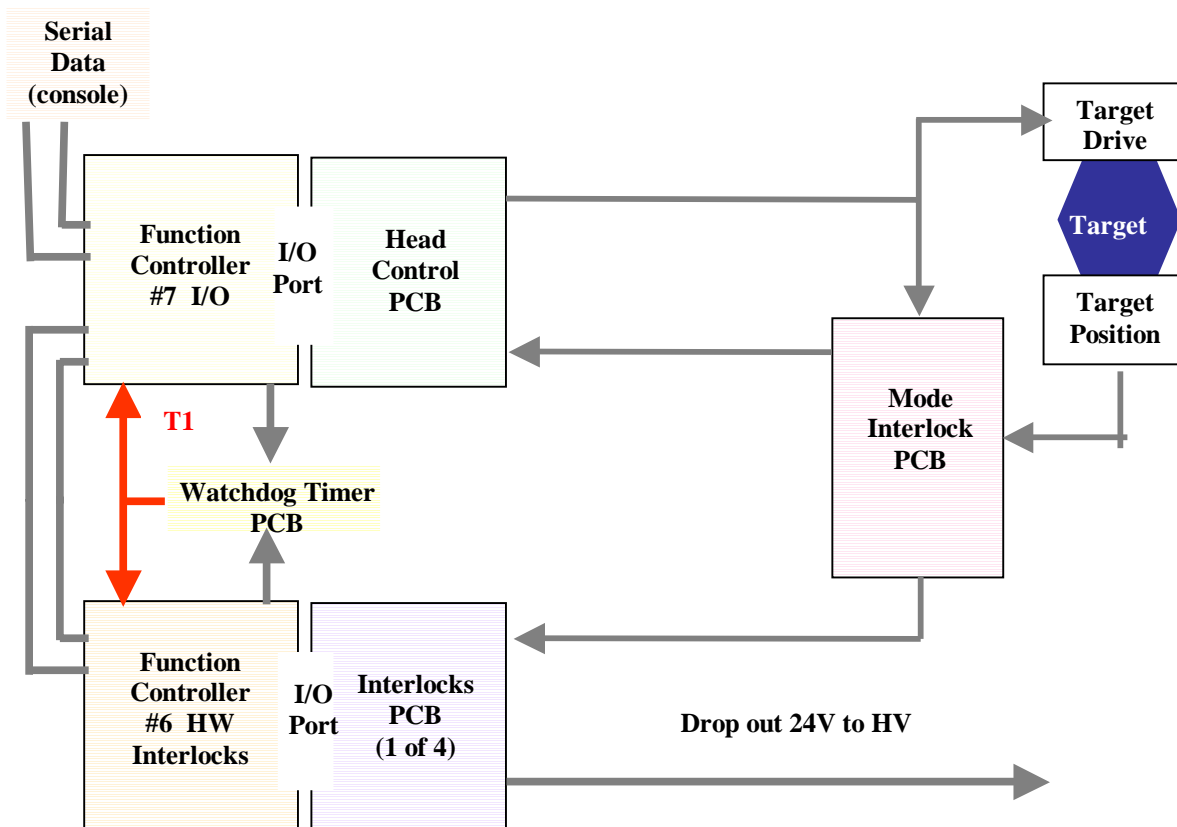


**Figure 8:** Siemens Primus I/O example, partial dosimetry channel block diagram.

## MODE SELECTION

The Primus is a standing-wave accelerator linac, therefore, the energy spectrum exiting the accelerator structure is dependent primarily upon the level of microwave power applied, and how that is "loaded" by the injection current. In terms of microwave frequency, the system operates at resonance, at which maximum power is transferred to the accelerator. Microwave power level is adjusted by means of setting the magnetron or klystron excitation current for the energy selected. Beam loading is a function of injection current. These are both fixed parameters for each beam. The control values for these and other machine parameters are stored in the control console in EPROM in the form of "softpots". Softpot data are transmitted to the function controllers as part of the mode selection sequence to set up various gains and values to configure the machine hardware. Final energy spectrum selection is made by the bending magnet, a 270° sector with fixed slits at the point of maximum dispersion. These slits serve to block the unwanted highest and lowest energy spectra. Here the current to the bending magnet coils determines the trajectory of a particular energy through the bending magnet, and so energy selection is adjusted by means of bending magnet current. The beam exits the bending magnet through a thin metal window. Immediately downstream of the exit window is the target slide, the bar that carries primary electron foils and the gold target is positioned by crossplane motion. Distal to the target is the filter slide/primary collimator, which positions the single secondary electron foil or one of the two flattening filters and the primary collimator in the beam via inplane translation. Lastly, one of two ion chambers (photons or electrons) is positioned in the beam by inplane translation of the chamber slide.

Positions of these devices are monitored by microswitches and détentes in the carriers. Control of the positioning of each is transmitted from the console to function controller #7 (I/O) to the Head Control PCB, which generates the motor drive commands, monitors results and transmits status back to the SIP through function controller #7. Interlock status of the target, filters and so on is decoded by the Mode Interlock PCB, which also receives drive information from the Head Control PCB. This interlock status is reported to the Head Control PCB, and to one of the four Interlock PCBs, which in turn activate or deactivate the hardware interlock chain and report status to function controller #6 (HW interlocks). Function controller #6 then transmits this status to the SIP for console display. Depending upon the status of the interlock and the machine state when it occurs, function controller #6 might also cause a watchdog timeout, resulting in T1 becoming active and terminating beam if necessary.



**Figure 9:** Siemens Primus target control and interlock scheme. Mode selection initiation is sent via function controller #7 to the Head Control PCB. The Mode Interlock PCB monitors status and activates an interlock if necessary. The interlock is implemented in hardware via the Interlocks PCBs, and in software via function controller #6 and the T1 line.

## BEAM CONTROL

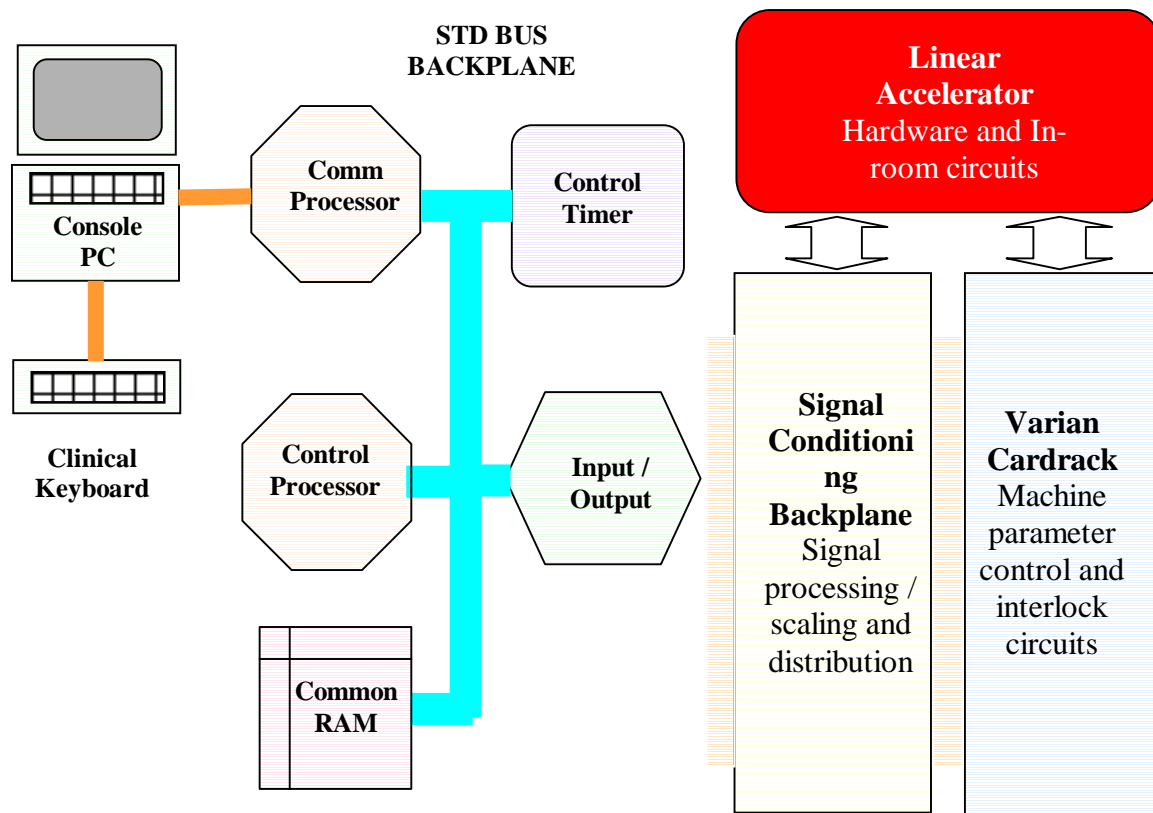
In the Primus, a gun/injector pulse is generated for every HV/microwave pulse. Use of the grid in the triode gun allows rapid switching of the injector current. Immediately after HV, there is a run-up period of 2 to 6 seconds, during which the HV and RF are allowed to stabilize. During run-up, the trigger for the injector is occurring out of phase, or non-coincident in time with the RF pulse; this produces no accelerated beam pulse, but may produce some dark current. A defocusing lens coil around the proximal end of the accelerator is used to suppress dark current. At the end of run up, the injector pulse is made coincident with the RF pulse, producing beam. Dose rate is controlled by adjusting the machine triggers PRF. It is servoed by adjusting PRF to maintain a constant dose rate as measured on dosimetry channel #2.

In IMRT mode, a PAUSE state is used to halt beam production while the necessary beam modifiers (MLC, gantry, etc.) are moved into place. During pause, the injector pulse is made non-coincident with the RF pulse, HV remains on, and the HV amplitude is reduced to 80% of nominal to suppress dark current.

## VARIAN

### DESCRIPTION OF MACHINE

The Varian 21-EX is a dual-photon standing-wave linear accelerator. The microwave system is klystron based, and the electron injector is a triode (gridded) type. The bending magnet is a 270° sector. Electron flattening is accomplished through dual foil scattering. A carousel is used to position scattering foils for up to 5 electron beams and 2 flattening filters for mode selection. A dual-channel fixed segmented ionization chamber is used for dosimetry monitoring.



**Figure 9:** Varian 21EX control system overall architecture.

## CONTROL SYSTEM ARCHITECTURE

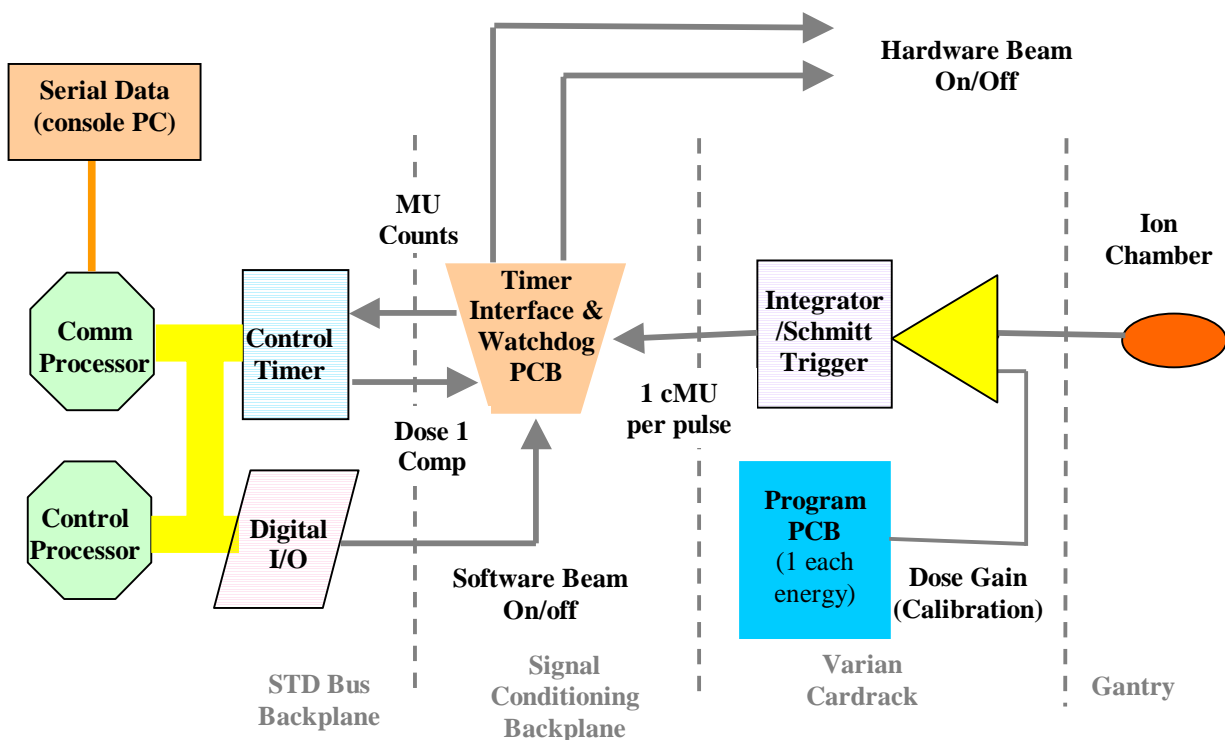
The Varian control system utilizes two Intel X86-based processors and timing on a STD Bus as the core for the Clinac control system. Figure 10 shows an overall diagram of this control system. These processors are the Communications Processor and the Control Processor. Both of these processors run programs stored in firmware. The Communications Processor handles communications between the control system and the machine hand and couch controls, the Console PC, and the gantry display unit. The Control Processor is the linac controller proper, and it sends commands to the circuits that make up the linear accelerator and processes information coming from them, via the programmable timers and general purpose I/O on the STD Bus. These two processors share a common block of RAM memory in which status of parameters and interlocks of system are posted. Each processor may fetch or modify data from the common RAM area in the course of normal operations, modifying a status byte associated with each location upon doing so. Commands from the console are posted in common RAM by the Comm Processor, then acted upon by the Control Processor. Results of the Control Processor actions are posted in common RAM for the Comm Processor to transmit to the console. The other critical circuit on the STD Bus is the Control Timer PCB. This is a 20 channel programmable timer through which the control system performs dosimetry monitoring and interlock generation, position readout timing and machine triggers generation. Signals coming to and from the STD bus units are processed through the Signal Conditioning Backplane, which, as the name implies, acts as a scaling and conditioning interface for I/O to the STD bus. The Varian Cardrack contains circuits specific to the setup, operation and interlock generation for the machine. Signal flow to the machine is both through the Signal Conditioning Backplane and the Varian Cardrack. Signal flow to the STD Bus circuits from the machine and the Varian Cardrack is through the Signal Conditioning Backplane. An Intel-based desktop PC serves as the operator interface for the machine. Configuration data and event logs are stored on the hard disk on this PC, as are the programs necessary for this unit to perform operator interface functions. Operator control of the machine is through a dedicated keyboard unit that communicates with the console PC through a serial port and is connected directly to the beam –on hardware through a keyswitch enable and hardware beam-off circuit.

## MODE SELECTION

The 21EX is a standing-wave accelerator linac, therefore, the energy spectrum exiting the accelerator structure is dependent primarily upon the level of microwave power applied, and how that is "loaded" by the injection current. In terms of microwave frequency, the system operates at resonance, at which maximum power is transferred to the accelerator. Microwave power level is adjusted by means of setting the klystron to operate as a class A (linear) amplifier. In this mode the power output is a function of power input, and so adjusting the power level of the RF driver controls power out of the klystron. Another means of controlling energy in the 21EX is through the use of an energy switch. The energy switch drives a plunger into one of the accelerator side cavities approximately 1/3 from the gun end. This effectively turns the remaining 2/3 of the accelerator into a drift tube, and little acceleration takes place.



Use of the energy switch allows a much higher power level to be applied to an effectively shorter accelerator. This permits acceleration of much higher beam currents needed to achieve the nominal dose rate of 600 MU/min. Final energy spectrum selection is made by the bending magnet, a 270° sector with fixed slits at the point of maximum dispersion. These slits serve to block the unwanted highest and lowest energy spectra. Here the current to the bending magnet coils determines the trajectory of a particular energy through the bending magnet, and so energy selection is adjusted by means of bending magnet current. The dual tungsten target assembly is mounted on a vacuum bellows so as to allow it to be pneumatically positioned with either the high-X or low-X target in the beam or withdrawn for electron mode. The beam exits the bending magnet through a thin metal (Be) window. Immediately downstream of the exit window is the fixed primary collimator. Distal to the primary collimator is a carousel that rotates the proper flattening filter or dual foil filter into place. Lastly, the fixed dual channel ion chamber monitors dosimetry. Positions of these devices are monitored by microswitches and détentes in the carriers. Control of the positioning of each is transmitted from the console to the Carousel and Mode Control PCB, where an FPGA decodes the switch positions with respect to the selected energy, and generates an interlock if necessary.



**Figure 11:** Varian 21EX hardware/software implementation of beam control and dosimetry, partial layout of dosimetry channel 1.

The interlock status is transmitted to the Timer Interface PCB on the Signal Conditioning Backplane where it disables the HV enable lines via hardware. It is also input to the Control Processor via the Signal Conditioning Backplane and STD bus I/O, and the interlock status is posted to common RAM, read by the Comm Processor and transmitted to the Console PC for display. The mode selection command is initiated as a 4-line BCD code from the Control Processor this is buffered to the Signal Conditioning Backplane via STB bus I/O and distributed to the Varian cardrack, gun control chassis, modulator, and carousel/mode control PCB to program each subsystem as needed. Program PCBs in the Varian cardrack are relay-switched in response to the BCD code to connect a number of potentiometers into the circuitry necessary to select the correct control parameters for the desired energy, such as PFN voltage, injector current, dosimetry calibration and beam steering. If the correct values are not read back from all control elements within 30 seconds of the mode command, an interlock is generated by the carousel/mode control PCB.

## BEAM CONTROL

In the 21EX the use of the grid in the triode gun allows rapid switching of the injector current. The microwave system and injector are operated at a constant PRF, 360 PPS for low-X and 180 PPS for high-X. At nominal max dose rate of 600 MU/min, this yields approximately 0.03 and 0.06 MU/pulse for low-X and high-X, respectively. Dose rate is controlled on a pulse-to-pulse basis by making the injected pulse timing either coincident or delayed with respect to the RF pulse timing. During the delayed injector pulse periods, dark current is suppressed by the focussing solenoid that encloses the accelerator. Dose rate is selected by delaying some or all of the pulses in a 6-pulse train. Maximum dose rate is achieved when all 6 of the pulses in the train are coincident. The dose rate servo functions by delaying pulses based on dosimetry data during a 50-mSec control window. Once the proper dose has been recorded during a control window, the remainder of the injector pulses are delayed for that window. In IMRT or dynamic beam delivery mode, the time aspect of the control window is simply replaced with some other segmented input, such as MLC position, gantry angle for arc therapy, photon jaw position for dynamic wedge, or gating input for gated therapy. In all modes, cMU dose counting occurs in the timer interface and control timer PCBs. The selected dose rate and dose information is used by the Control Processor to program the control timer to monitor dose, dose rate, dosimetry interlocks, etc. During beam on, the Control Processor compares the desired MU count to the current MU delivery, and when the two are equal, sends a complete signal to the control timer, which then terminates beam via hardware and software paths through the timer interface PCB. The control timer also performs the dose rate servo and dose rate counting functions.

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