Oxford Linac control signal handling

1. Introduction

The Oxford Gray Institute Linac is controlled entirely by a host PC through USB connections. There are two USB links: one is used to control the accelerator in its Faraday cage (the 'machine'), the other is used to control various deflection magnets to route the electron beam to one of three irradiation stations. The 'machine' USB link is realised with the aid of an optical extender unit, which converts USB data to a duplex optical fibre cable which carries information to an optical receiver unit placed inside the linac's Faraday cage. In fact this unit is placed inside a secondary screened enclosure which houses most of the data acquisition circuitry. The 'magnet' USB link is realised using conventional copper cable, though this is also makes use of bus extender modules, using RJ45 cable connecting the transmitting and receiving modules.

Internally in each of these systems, the USB port is converted to an I^2C bus which is daisy-chained as required to a several data acquisition and data setting modules. The I^2C bus as originally developed by Philips for 'Inter-Integrated Circuit' applications in consumer and other applications. is very convenient to achieve inter-instrument control at moderate speeds (http://en.wikipedia.org/wiki/I2C, http://www.i2c-bus.org). The bus protocol is extremely rugged. The interface electronics have already been described in a companion application note "USB1 communications interface for controlling instruments" (http://users.ox.ac.uk/~atdgroup/).

We describe in this note the arrangement used to convert I^2C data streams into analogue voltages or digital control signals as well as how analogue and digital signals are converted into I^2C data. All the circuitry is constructed on 'Eurocard' 100 x 160 mm cards using 64 way DIN14612 card connectors.

2. EMI protection

Electron linear accelerators are well known for the tremendous amount of electrical interference which they generate, primarily due to the circulation of high current pulses associated with their magnetron modulators. The control systems in such machines are usually placed well away form the modulators and often outside the room where the modulators are placed. In our case, we wanted all the electronics directly associated with the accelerator to be relatively close to the machine body so that 'everything' could be placed inside a Faraday cage, thus minimising any leakage of interference to experimental areas.

This created a few challenges but these were overcome by paying attention to the routing of high current paths and by using relatively standard techniques for minimising the consequences of radio-frequency interference. This included the use of RFI-filtered connectors and optical isolation techniques for all low-power data acquisition signals. All components associated with the USB link internal to the machine are placed inside a screened enclosure with all inputs/outputs appropriately filtered, including the AC mains power connection.

3. Logic signal interfaces

3.1 DC power supplies and signal levels

In most cases logic outputs are used to turn on or off different subsystems of the accelerator and the loads switched are usually powered by 240 V ac. The switching is performed with 24V ac contactors. In some cases a low-power logic output may drive a 'volt-free' contact or similar low power load. It is also worth pointing out that during testing or fault-finding, particularly when software testing is required, it is highly desirable to be able to permanently switch on or off a particular output manually. Of course only trained personnel can do this, as defined by local operating rules.

The linac features a 24 V ac and a 24 V dc power supply bus and we have thus used a circuit arrangement shown in Figure 1. Low level logic signals are first optically isolated using a Phoenix Contact DEK-OE-5DC/24DC/100KHZ isolator where they are converted to 24 dc logic levels. These feed a relay module, Octo HAR1, which has a built-in switch to allow on, off or controlled relay operation. The outputs of these relays go on to drive the 24 V ac powered load, eventually turning on or off the relevant contactors associated with the linac power circuitry.

The monitoring of the state of a 24 V ac circuit is performed with an Octo OSK1 relay, its contacts driving low-level logic directly.

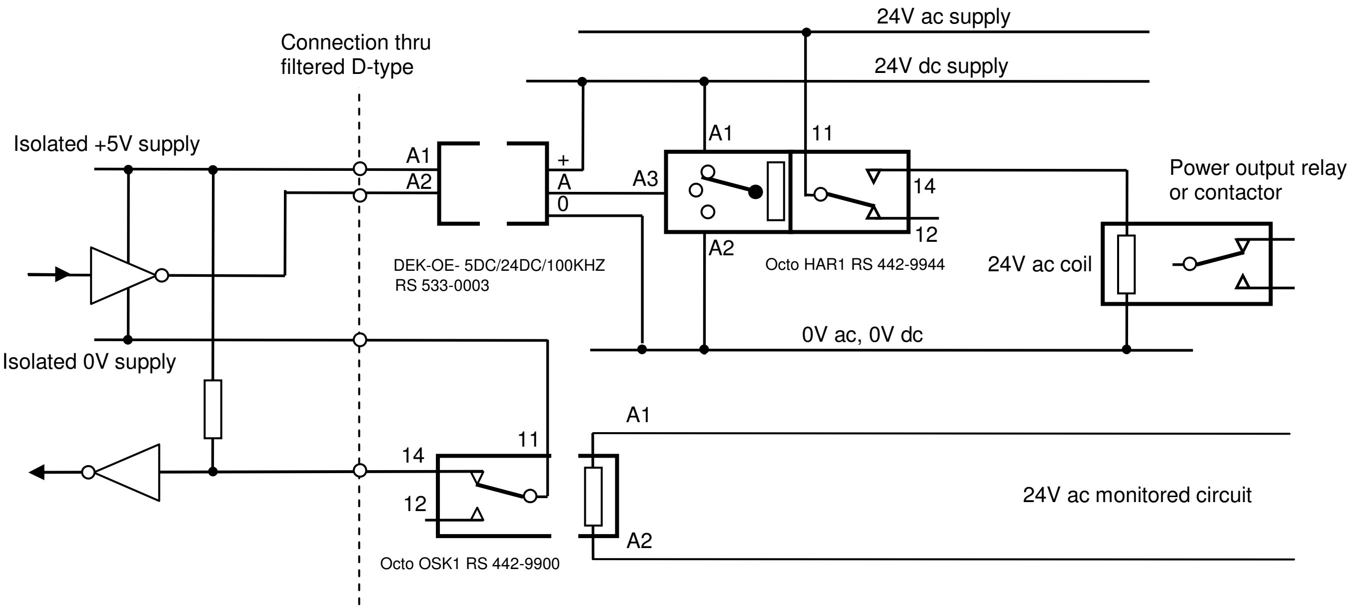


Figure 1: Generic logic input and output interface circuit

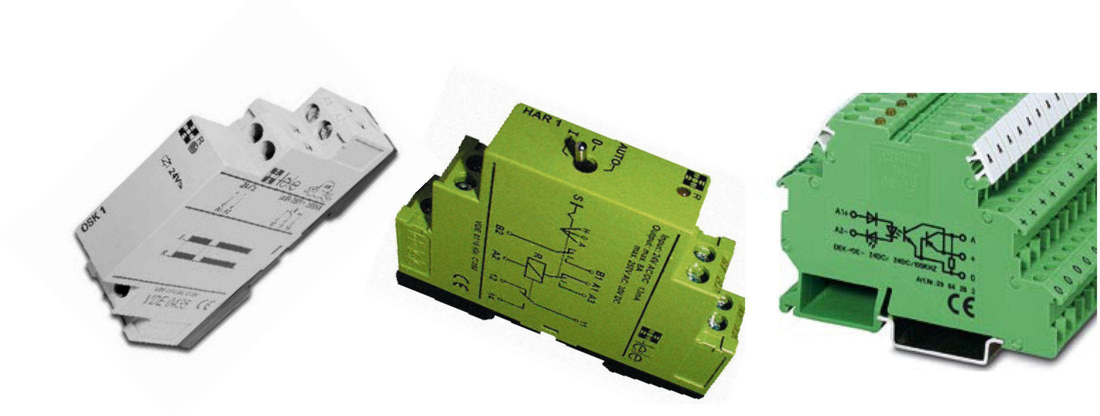


Figure 2: The DIN-rail mounted optoisolators and controlled relay modules

These modules are shown in Figure 2. They can be conveniently mounted on a DIN rail. DC circuits are monitored with the Phoenix Contact DEK-OE- 5DC/24DC/100KHZ optical isolators.

3.2 Water flow and waveguide pressure

There a numerous subsystems in the accelerator which require water cooling. The distribution of water flows and pressures is controlled with internal valves and appropriate pipe diameters. However, the presence of cooling water pressure is sensed with pressure switches. Rather than remotely monitoring the output of every pressure switch, we make use of the fact that they are fitted with changeover switches: one side drives a local indicator while the other terminals are ‘OR’ed such that if any flow switch ‘disconnects’ a relay coil is energized signaling to the remote interface a water fault. When the operator investigates, local indicators will show the status of the fault.

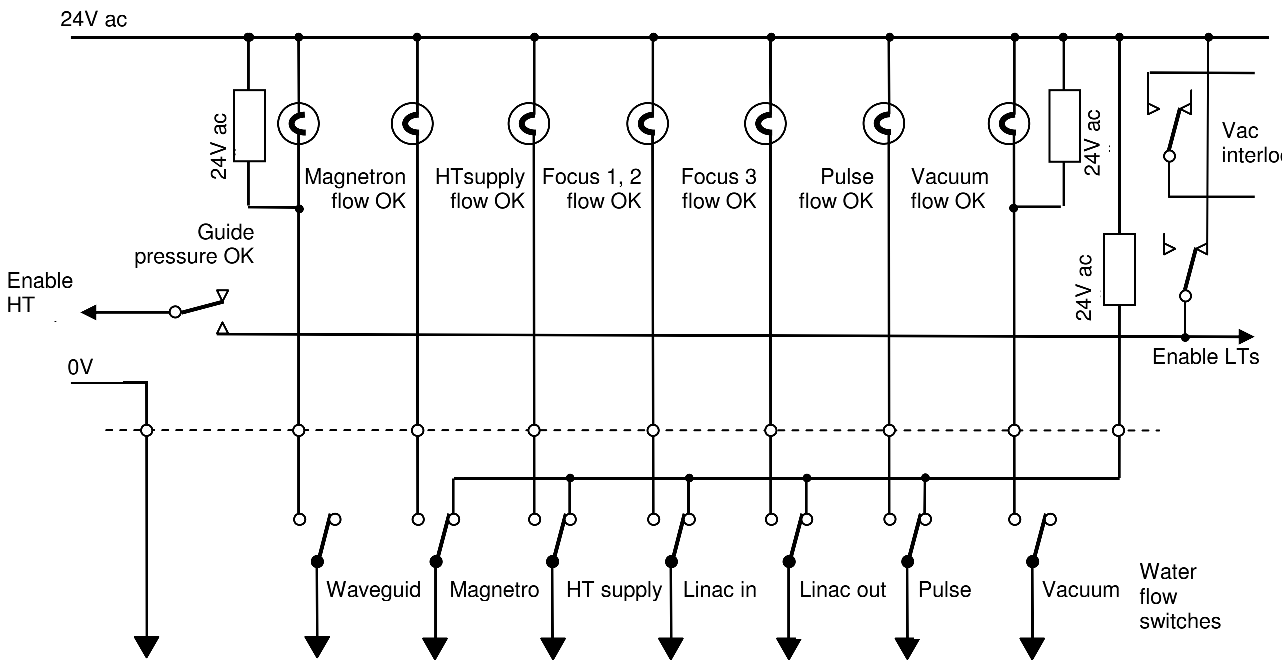


Figure 3: Water cooling and pressure interlock

The only exception is the vacuum system water cooling circuit. When the water cooling is present, it is used for cooling the turbo-molecular vacuum pumps. When water cooling is not present (i.e. when the machine is off), an interlock circuit switches on air fans which then provide cooling. These are switched off when water is available.

The linac's waveguides must be pressurized to avoid arcing during the delivery of the radiofrequency pulse. If waveguide pressure is not present (or low) a waveguide pressure switch deactivates disabling the HT modulator power supply.

3.3 Practical implementation

The various relays and opto-isolators described above are arranged on a DIN rail near the front of the machine control rack. This arrangement is shown in Figures 4 and 5; devices controlling the machine and devices providing feedback to the host are grouped together to make servicing straightforward.

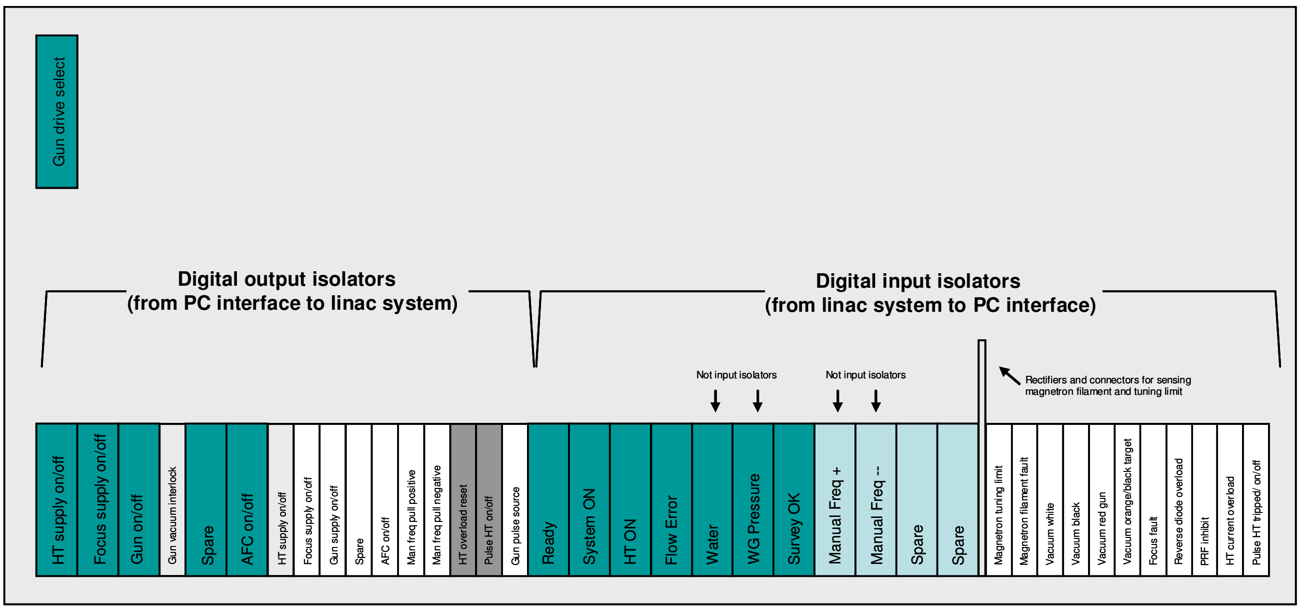


Figure 4: Diagram of opto-isolators and relays on DIN rail.

Figure 5: Practical arrangement of opto-isolators and relays on DIN rail; Flow and waveguide pressure switches can be seen in the lower image.

3.4 Logic interface circuit

The opto-isolators and relays shown in Figures 2-5 are controlled and sensed with a 5V logic interface, shown in Figure 6. Here we use 3 eight bit I^2C ports, PCF 8574 for sending logic signals to the linac and 3 further PCF 8574 eight bit I^2C ports for sensing logic state data. The outputs of the PCF8574s are buffered with 8 bit buffers (74HCT541s). Logic inputs are buffered with 8 bit inverters (74HCT540s). We thus have 24 bits of input and 24 bits of output logic data available.

The PCF8574 chips are available in two address banks, as types PCF8574 and types PCF8574A. In order to simplify programming, addresses 0, 1, 2 are used for both input and output and we arranged the wiring to ‘match’ input and output channels: if a device is turned on with channel OUT12 for example, we arrange that the device is monitored with channel IN12.

Although the PCF8574s provide an interrupt line which is activated on any input change, we do not make use of this facility, preferring a polling type software arrangement which also functions as a simple watchdog type timer. In this way we are sure that all circuits have been ‘seen’.

The dc input to this board is locally regulated to +5V and appropriate pull-up and input/output protection resistors are used to connect to the off-board circuitry, as described above.

For simplicity optoisolators are shown on only two of the input and output channels in Figure 6. Of course they are used on many of the inputs. Where they are not used, relay contacts are connected instead of the A and 0 optoisolator pins.

The logic lines are connected to two filtered 25 way D-typpe sockets, forming the interface between the internal screened enclosure and the rest of the accelerator. Sockets with ~1 nF from each pin to socket frame are used and have been found adequate to prevent any linac-generated interference from affecting the operation of the logic circuits.

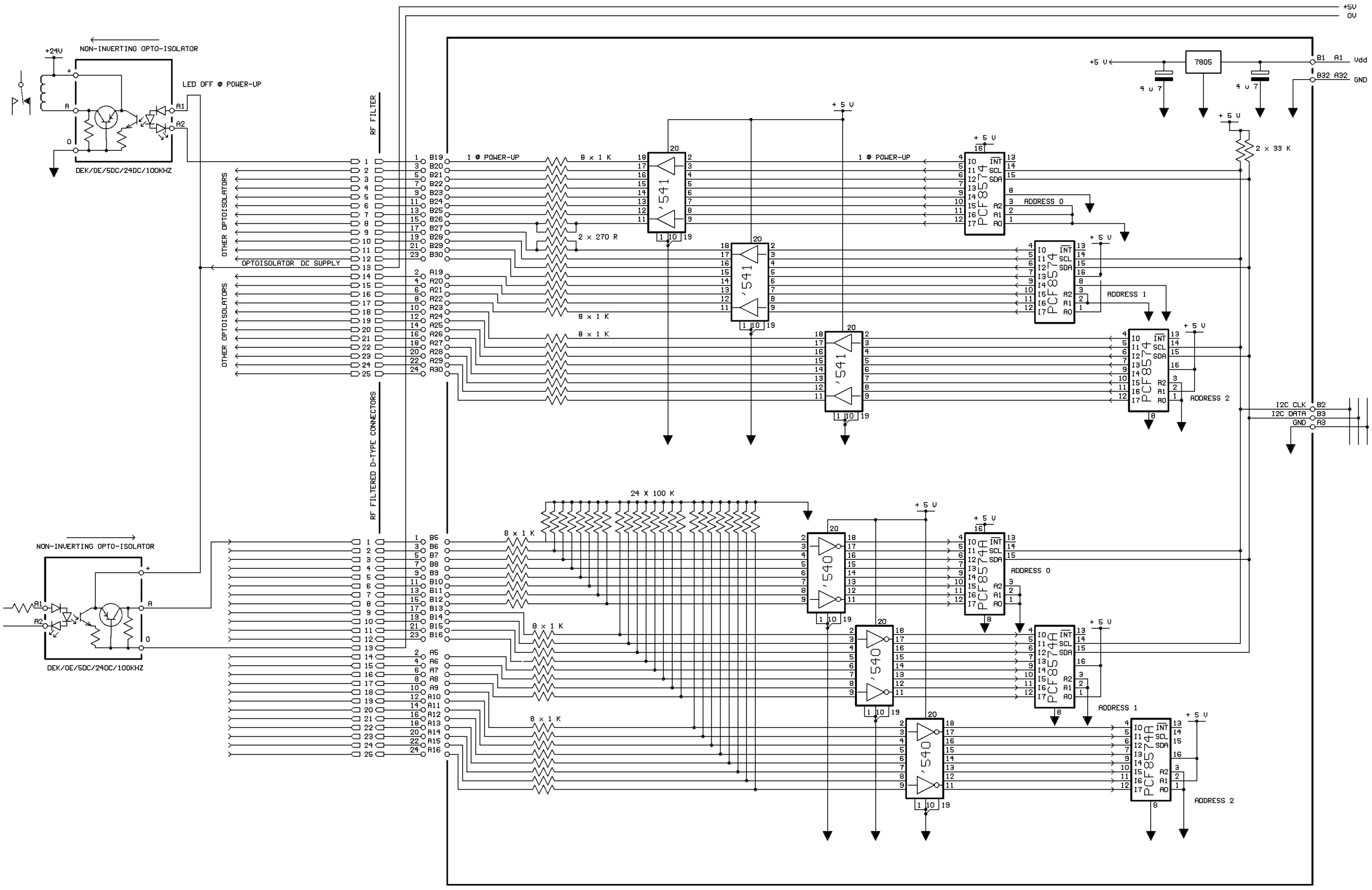


Figure 6: The logic circuit interface board

A list of the control and monitoring channels is provided in the table below. We have provided several spare channels in both directions should future enhancements be required; it is much simpler to provide these at time of construction than later!

Digital channel number	Signal from controller logic / from control PC / USB interface	Range	Quiescent state	D type signal hi pin #	Isolation direction
0	Energise main HT power supply	0-+24 V DC	Hi (off)	1	→
1	Energise Focus power supply	0-+24 V DC	Hi (off)	2	→
2	Energise Gun power supply	0-+24 V DC	Hi (off)	3	→
3	Spare	n/a	Hi	4	→
4	Select manual freq. control	0-+24 V DC	Hi (Manual)	5	→
5	Manual freq drive up	0-+24 V DC	Hi (no drive)	6	→
6	Manual freq drive down	0-+24 V DC	Hi (no drive)	7	→
7	Reset main HT overload	0-+15 V DC	Hi (non-reset)	8	→
8	Pulse HT power supply inhibit	Weak + logic	Hi (off)	9	→
9	Select Gun drive type	0-+24 V DC	Hi (Single shot)	10	→
10	Spare	n/a	Hi	11	
11	Spare	n/a	Hi	12	
	+5 DC SUPPLY		+5 DC SUPPLY	13	
12	Spare	n/a	Hi	14	
13	Spare	n/a	Hi	15	
14	Spare	n/a	Hi	16	
15	Spare	n/a	Hi	17	
16	Spare	n/a	Hi	18	
17	Spare	n/a	Hi	19	
18	Spare	n/a	Hi	20	
19	Spare	n/a	Hi	21	
20	Spare	n/a	Hi	22	
21	Spare	n/a	Hi	23	
22	Spare	n/a	Hi	24	
23	Spare	n/a	Hi	25	

Digital channel number	Signal to controller logic / to control PC / USB interface	Range	Quiescent state	D type signal hi pin #	Isolation direction
0	AFC limit switch monitor	+ / - 24V	0 V (no fault)	1	←
1	Vacuum gauge 1, trip 1	0 - +15 V	0 V (no fault)	2	←
2	Vacuum gauge 2, trip 1	0 - +15 V	0 V (no fault)	3	←
3	Focus out of range detect	0 - +15 V	+15 V (no fault)	4	←
4	PRF inhibit detect	0 - +15 V	0 V (no fault)	5	←
5	System is ready	24 V AC	24 V AC (when ready)	6	←
6	Main HT is on	24 V AC	0 V AC (HT is OFF)	7	←
7	Single Pulse HT tripped	Weak logic		8	←

8	Spare	n/a	n/a	9	
9	Spare	n/a	n/a	10	
10	Spare	n/a	n/a	11	
11	Spare	n/a	n/a	12	
	DC SUPPLY GROUND		DC SUPPLY GROUND	13	
12	Magnetron filament fault	24 V AC	0 V AC (no fault)	14	←
13	Spare for Vacuum gauge 1, trip 2	Not used	Not used	15	←
14	Spare for Vacuum gauge 2, trip 2	Not used	Not used	16	←
15	Reverse diode overload detect	0 - +15 V	+15 V (no fault)	17	←
16	Main HT overload detect	0 - +24 V	+24 V (no fault)	18	←
17	System is on	24 V AC	24 V AC when ON	19	←
18	Flow error	24 V AC	0 V AC (no fault)	20	←
19	Survey OK	24 V AC	24 V AC (surveyed)	21	←
20	Spare	n/a	n/a	22	
21	Spare	n/a	n/a	23	
22	Spare	n/a	n/a	24	
23	Spare	n/a	n/a	25	

4. Analogue signal interfaces

4.1 Signal isolation

Numerous sub-systems within the linac require analogue control of setpoints and provide analogue readback information. These data also require isolation and this has been achieved using HPCL7840 isolators. These devices are designed to handle isolation voltage swings of several hundred volts in tens of nanoseconds and are capable of ignoring very high common-mode transient slew rates (of at least 10 kV/μs). Although originally intended for motor control applications, they can also be used for general analog signal isolation applications requiring high accuracy, stability, and linearity s. The HCPL7840 utilizes sigma delta (Σ-Δ) analog-to-digital converter technology, chopper stabilized amplifiers, and a fully differential circuit topology and their low cost allows the use of multiple devices, one per each channel. In addition, they have a remarkable input sensitivity, capable of processing signals down to a few hundred millivolts full-scale input. They are thus well-matched for sensing high currents through very low value current sense resistors, without requiring further amplification before isolation. Higher input voltages are handled using a voltage attenuator at the input. Further data is available on http://www.avagotech.com/pages/en/optocouplers_plastic/plastic_miniature_isolation_amplifier/hcpl-7840/. The output range is defined by resistors used around an operational amplifier at the back of the HPCL7840.

We designed a circuit board which contains twelve isolated channels, arranged in such a way that the board can be used to isolate signals to the controller and *vice-versa*. In addition, the outputs can be arranged to be unipolar non-inverting, unipolar inverting or bipolar, depending on which operational resistors are fitted; the sensitivity can similarly be adjusted on each channel.

The circuit diagram of the arrangement is shown in Figure 7. Very low offset voltage dual opamps (Linear Corp. LT1366, http://www.linear.com/product/LT1366) are used to minimize the need for extensive post-acquisition software calibration (though this is used). Inspection of Figure 7 will show that the board is fitted with a power regulator on the output side (LM2941, http://www.national.com/mpf/LM/LM2941.html#Overview) which can be disabled when the board is used to sense signals from the machine, and enabled when the board is used to provide analogue data to the machine setpoints. A single design of printed circuit board makes life 'easy' and a symmetrical layout allows boards to be stacked. The board layouts are shown in Figure 8 and their construction within the linac control cabinet is shown in Figure 9.

Once again, we have provided several spare channels, for possible future expansion. Currently, the channels are allocated as shown in the table overleaf. This table also indicates whether the channel is configured as unipolar or bipolar and the values of the resistors used around the LT1366 operational amplifier. For a more thorough description of the operation of the isolator-operational amplifier system, please refer to the HPCL7840 opto-isolator data sheet. When transferring signals to the host PC, 0-+5V input analogue to digital converters are used and the output sensitivity is adjusted on this isolation board to match this analogue-to-digital converter signal range.

Analogue control and monitoring channel listing:

Analogue channel number	Signal to optoisolator DACs/ from control PC / USB interface	Range	Input quiescent level	Isolator output range	Isolator quiescent level	Range (fsd)	Typical or *maximum* controlled value	Sense resistor	Isolator input series resistor	Isolator input shunt resistor	Isolator output offset resistor	D type signal hi pin #	D type signal lo pin #
0	Steerer 1 current set (gun, 1T)	0 – +2V	+1 V	±1V	0 V	±0.5 A	± 0.44 A	1 Ω	3.9 kΩ	100 Ω	! -10 kΩ !	1	14
1	Steerer 2 current set (gun, 1R)	0 – +2V	+1 V	±1V	0 V	±0.5 A	± 0.44 A	1 Ω	3.9 kΩ	100 Ω	! -10 kΩ !	2	15
2	Steerer 3 current set (target, 2T)	0 – +2V	+1 V	±3V	0 V	±1.5 A	± 1.25 A	1 Ω	3.3kΩ+360Ω	300 Ω	! -10 kΩ !	3	16
3	Steerer 4 current set (target, 2R)	0 – +2V	+1 V	±3V	0 V	±1.5 A	± 1.25 A	1 Ω	3.3kΩ+360Ω	300 Ω	! -10 kΩ !	4	17
4	Focus 1 current set	0 – +2V	0 V	0 – +10V	0 V	0 – 40 A	29.52 A	4.17 mΩ	3.3kΩ+200Ω	500 Ω	∞	5	18
5	Focus 2 current set	0 – +2V	0 V	0 – +10V	0 V	0 – 40 A	25.44 A	4.17 mΩ	3.3kΩ+200Ω	500 Ω	∞	6	19
6	Focus 3 current set	0 – +2V	0 V	0 – +10V	0 V	0 – 40 A	30.24 A	4.17 mΩ	3.3kΩ+200Ω	500 Ω	∞	7	20
7	AC gun emission set	0 – +2V	0 V	0 – +5V	0 V	(0 – 10 A)	7.5 A	n/a	3kΩ+750Ω	250 Ω	∞	8	21
8	Pulse HT voltage set	0 – +2V	0 V	0 – +5V	0 V	0 – 20 kV	18 kV	n/a	3.3kΩ+200Ω	500 Ω	∞	9	22
9	Pulse width monostable control	0 – +2V	0 V	0 – +5V	0 V	2.5 V	n/a	n/a	3kΩ+750Ω	250 Ω	∞	10	23
10-11	Spare	---	---	---	---	---	---	---	---	---	---	11	24

Analogue channel number	Signal to ADCs from optoisolators / to control PC / USB interface	Range	Quiescent level	Isolator input range	Isolator overall gain	Range (fsd)	Typical or *maximum* operating value	Sense element	Isolator input series resistor	Isolator input shunt resistor	Isolator output offset resistor	D type signal hi pin #	D type signal lo pin #
0	Steerer 1 current monitor (gun, 1T)	0 – +5V	+2.5 V	± 500 mV	x 5	± 0.5 A	± 0.44 A	1 Ω	230Ω+680Ω	130 Ω	20↑ + 20↓	1	14
1	Steerer 2 current monitor (gun, 1R)	0 – +5V	+2.5 V	± 500 mV	x 5	± 0.5 A	± 0.44 A	1 Ω	230Ω+680Ω	130 Ω	20↑ + 20↓	2	15
2	Steerer 3 current monitor (target, 2T)	0 – +5V	+2.5 V	± 1.5 V	x 1.666	± 0.15 A	± 1.25 A	1 Ω	230Ω+3.9kΩ	180 Ω	20↑ + 20↓	3	16
3	Steerer 4 current monitor (target, 2R)	0 – +5V	+2.5 V	± 1.5 V	x 1.666	± 0.15 A	± 1.25 A	1 Ω	230Ω+3.9kΩ	180 Ω	20↑ + 20↓	4	17
4	Focus 1 current monitor (75 mV / 18 A)	0 – +5V	0 V	166.67 mV	x 30	0 – 40 A	29.52 A	4.17 mΩ	100 Ω	300 Ω	110↑+11↓	5	18
5	Focus 2 current monitor (75 mV / 18 A)	0 – +5V	0 V	166.67 mV	x 30	0 – 40 A	25.44 A	4.17 mΩ	100 Ω	300 Ω	110↑+11↓	6	19
6	Focus 3 current monitor (75 mV / 18 A)	0 – +5V	0 V	166.67 mV	x 30	0 – 40 A	30.24 A	4.17 mΩ	100 Ω	300 Ω	110↑+11↓	7	20
7	AC gun emission monitor (8V / 8A)	0 – +5V	0 V	10 V	x 0.5	0-10 A	9 A		10kΩ+270Ω	130 Ω	∞	8	21
8	Pulse HT voltage monitor	0 – +5V	0 V	10 V	x 0.5	0 – 20 kV	20 kV	n/a	100kΩ+2.7kΩ	1.3 kΩ	∞	9	22
9	Pulse HT current monitor	0 – +5V	0 V	10 V	x 0.5	0 – 10 mA	10 mA	n/a	100kΩ+2.7kΩ	1.3 kΩ	∞	10	23
10	Magnetron filament voltage	0 – +5V	0 V	-20 V	x 0.25	0- -20V	-6—8V	n/a	43 kΩ	270 Ω	10 kΩ +↑	11	24
11	Main HT current monitor	0 – +5V	0 V	-	x 0.4166	0- -1A	n/a	12Ω	15kΩ+200Ω	160 Ω	10 kΩ +↑	12	25
12	spare	---	---	---	---	---	---	---	---	---	---	1	14
13	Vacuum level 1 monitor	0 – +5V	0 V	10 V	x 0.5	logarithmic	10^{-5} T	n/a	10kΩ+270Ω	130 Ω	∞	2	15
14	Vacuum level 2 monitor	0 – +5V	0 V	10 V	x 0.5	logarithmic	10^{-5} T	n/a	10kΩ+270Ω	130 Ω	∞	3	16
15	AFC error output monitor	0 – +5V	0 V	± 10 V	x 0.25	± 10 V	± 1 V	n/a	43 kΩ	270 Ω	20↑ + 20↓	4	17
16	Water temperature	0 – +5V	0 V	1000 mV	x 5	0 – 100°C	50°C	10 mV/ °C	910 Ω	130 Ω	∞	5	18
17	Air temperature	0 – +5V	0 V	1000 mV	x 5	0 – 100°C	50°C	10 mV/ °C	910 Ω	130 Ω	∞	6	19
18-23	Spare	---	---	---	---	---	---	---	---	---	---	7	20

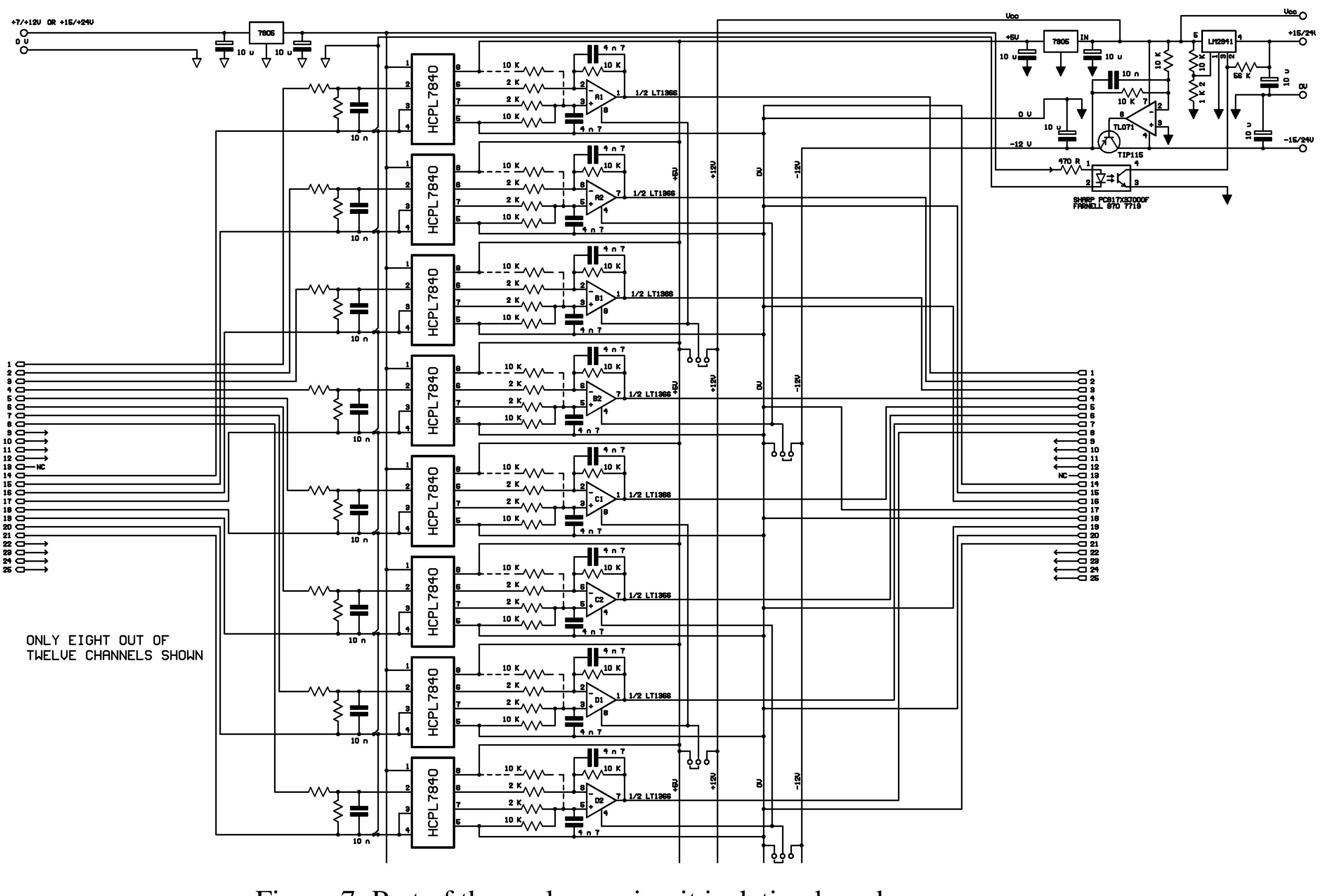


Figure 7: Part of the analogue circuit isolation board.

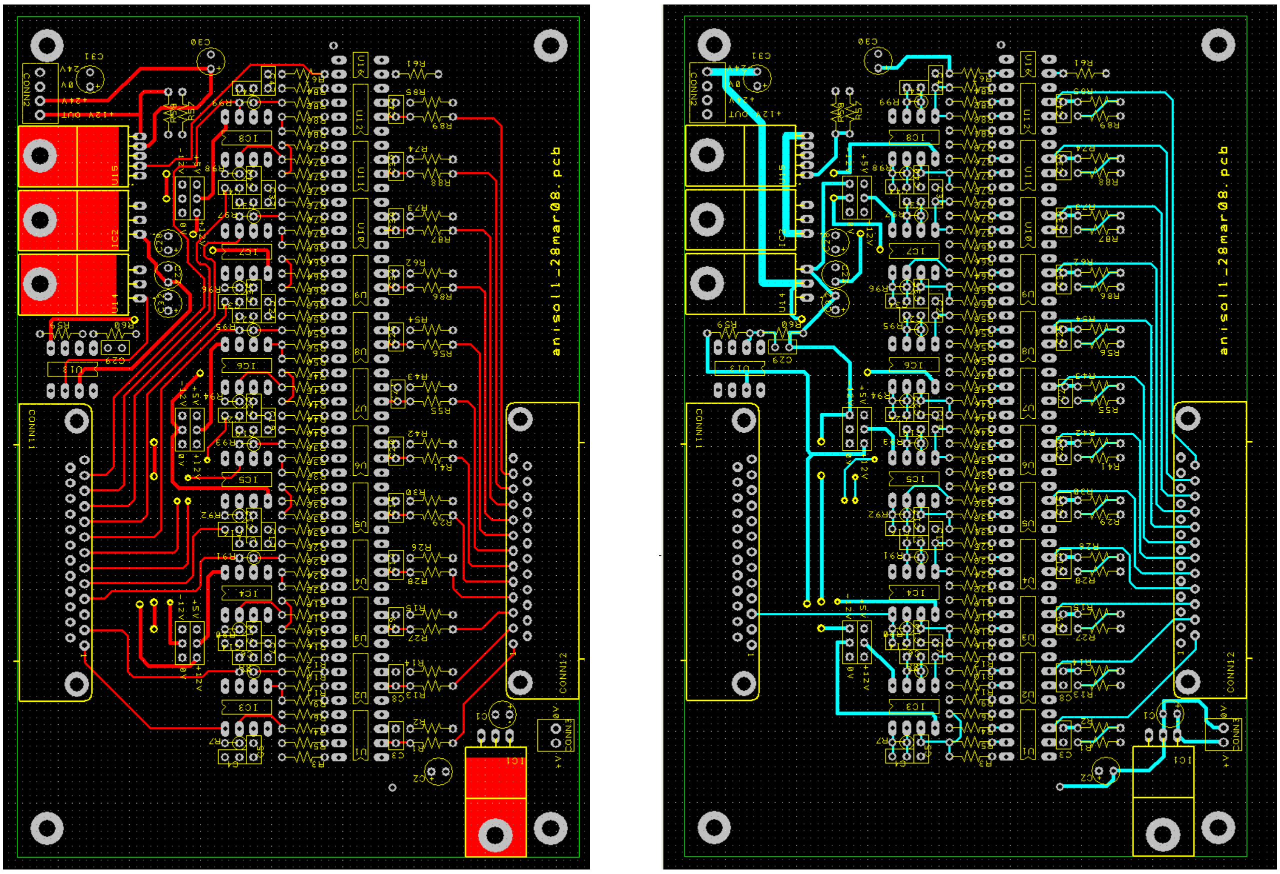


Figure 8: Analogue isolation circuit four-sided 150 x 100 mm printed circuit board. The component side is shown on the left, track side on the right; the middle layers are used as ground planes.

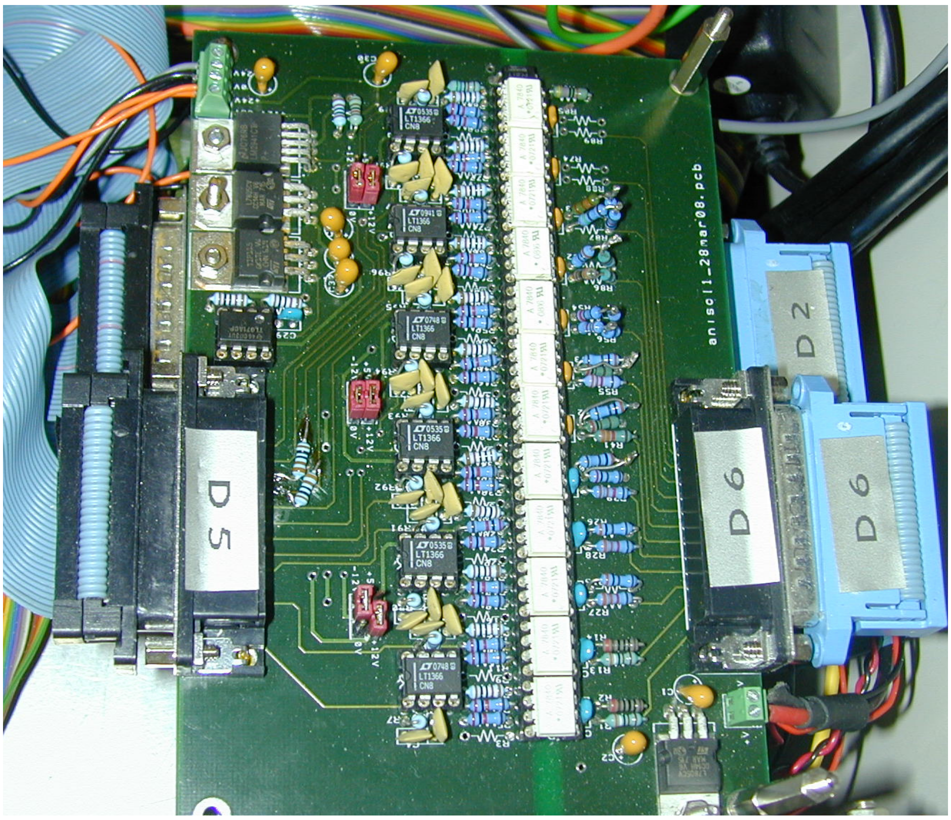


Figure 9: Analogue isolation circuit construction.

4.2 Analogue-to-digital and digital-to-analogue conversion

So far, only the isolation of the analogue signals has been discussed. We next describe how the signals are converted to digital data for processing by the host and *vice versa*. The analogue to digital conversion circuit board is shown in Figure 10. Here we make use of the versatile, though somewhat costly MAX127 data acquisition chips (http://www.maxim-ic.com/datasheet/index.mvp/id/1890). Three of these devices provide us with 12 bit resolution outputs on 24 channels (again spare channels are provided). These are wired with 3 addresses to provide I^2C data which is ultimately converted to a USB data stream, as described in our companion note "USB1 communications interface for controlling instruments" (http://users.ox.ac.uk/~atdgroup/).

Data flow in the other direction is provided by MAX521 (http://www.maxim-ic.com/datasheet/index.mvp/id/1251) 8 bit octal digital-to-analogue converters, as shown in Figure 11. We use two such boards, with the outputs wired to provide 12 bit resolution (though not 12 bit accuracy!) from I^2C data streams. A +4V reference is provided on each board, defining the maximum output levels. These voltages are summed in easily accessible resistor networks which feed the optical isolation boards. On one of the boards, a 74HCT4053 switch is provided to reduce the 'outputs' controlling the focus magnet power supplies: when the linac is idle, there is no need to energise the magnets, thereby saving several kilowatts of power.

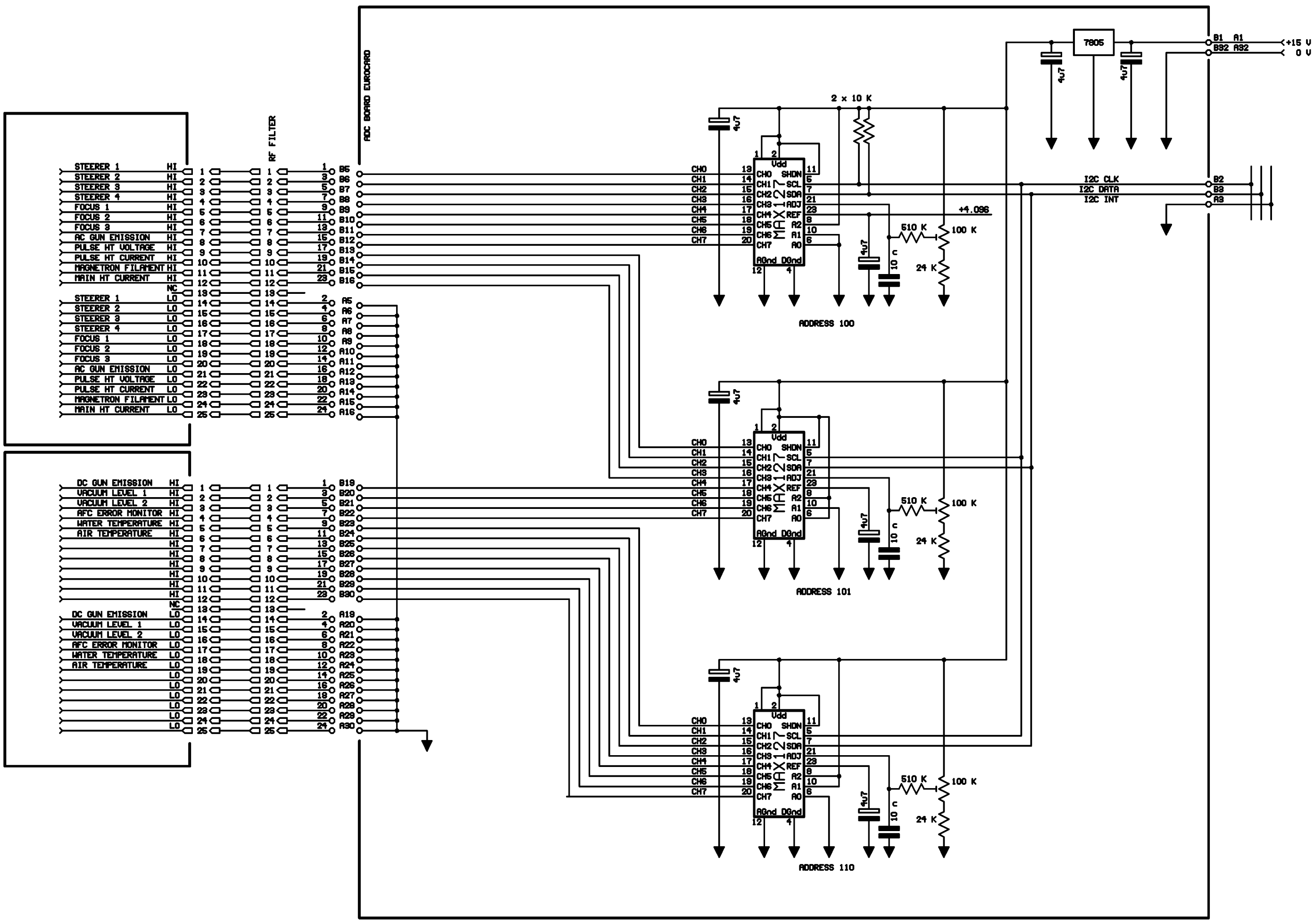
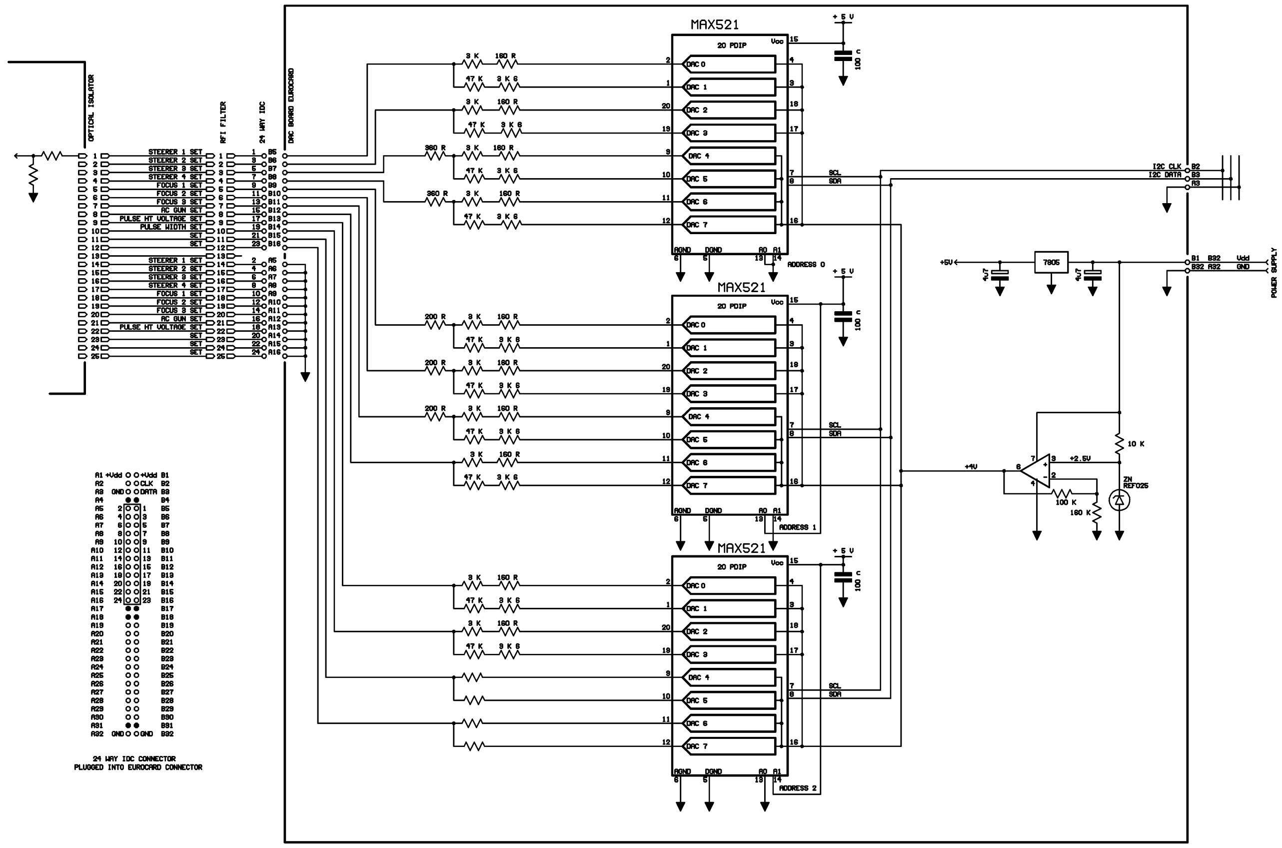


Figure 10: Analogue data acquisition board.



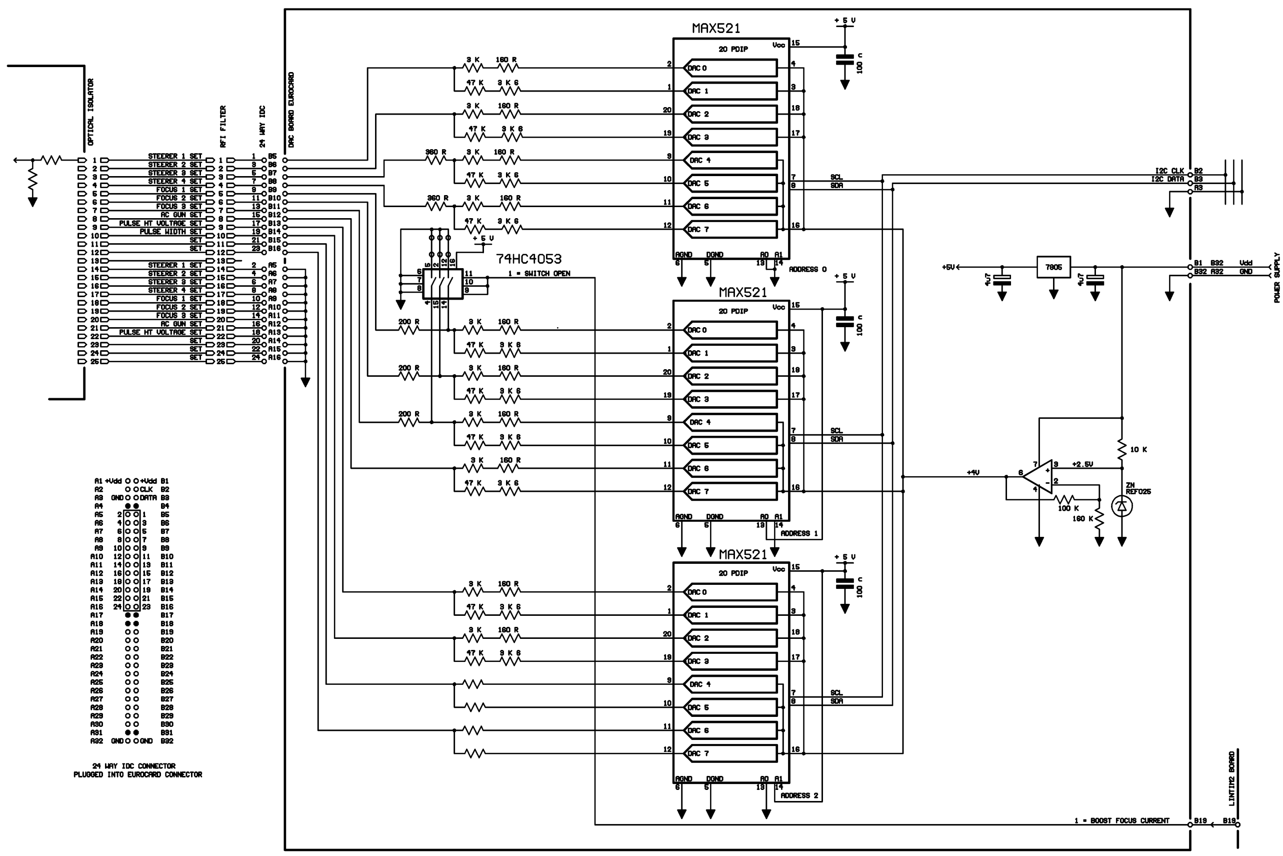


Figure 11: Analogue data setpoint boards.

5. Conclusion

The various circuit arrangements to control the linac and to determine its status, from analogue and digital data have been described here. The authors realise that the designs associated with this highly specific application may not be applicable for other instrumentation systems. Nevertheless it is hoped that some elements of the designs presented here may be valuable. Of course, there are numerous other ways that could have been used to implement this system. However, the modular approach described here has been found to be extremely reliable and was implemented at cost significantly lower than that associated with more 'ready-made' commercial solutions. The portions of the circuits housed inside the screened enclosure are shown in Figure 12.

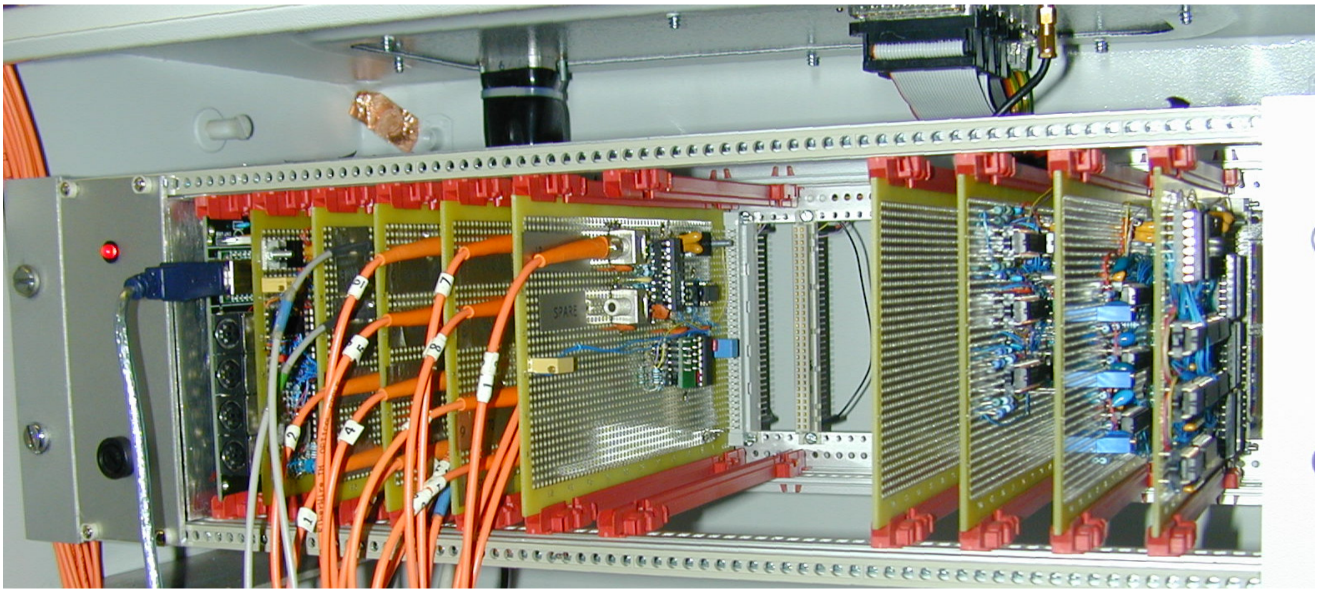


Figure 12: The low level linac electronics rack : to the left are fibre-optic transmitters/receivers handling timing data in and out of ther Faraday cage, while the data i/o system boards are to the right of the screened enclosure. The filtered D-type sockets can just be seen in the the top right of the image.

This note was prepared by B. Vojnovic and R.G. Newman in early 2012. The basic arrangement was designed by B. Vojnovic who heavily relied on R.G. Newman for putting it into practice. R.G. Newman designed the printed circuit boards and developed all of the low-level programming.

We acknowledge the financial support of Cancer Research UK and the Medical Research Council.