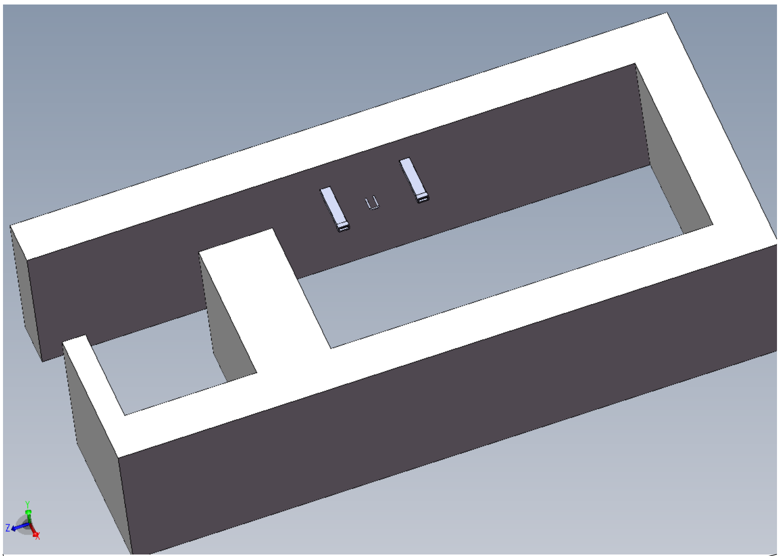
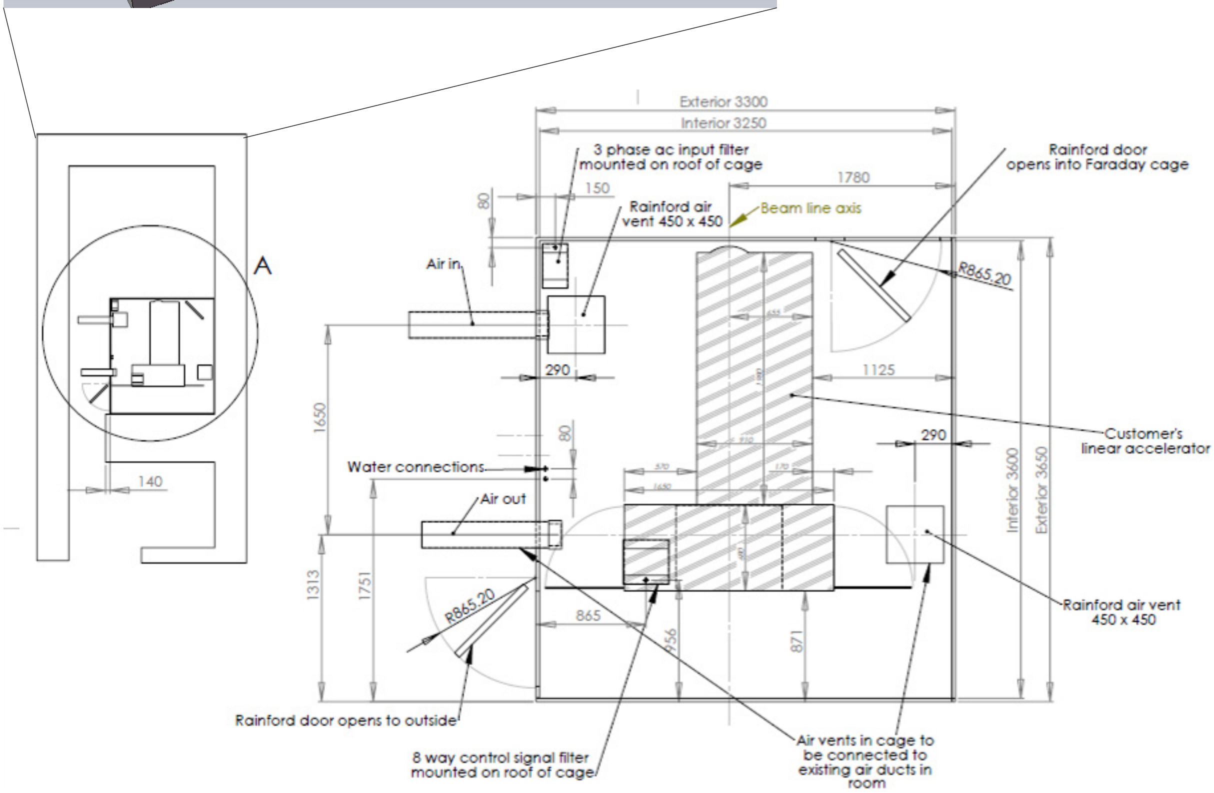
Development of the Gray Institute single pulse electron linear accelerator Part 2

The accelerator was transported to Oxford without any problems. The first task was to place it in the custom designed vault. In other words, we had a wonderful empty space at our disposal!

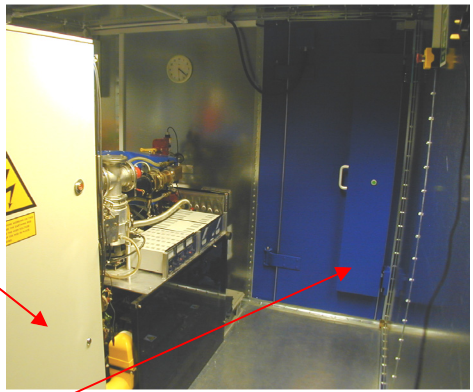
It is well known that linacs generate a tremendous amount of interference, generated primarily by the magnetron modulator. We had decided early on to place the accelerator inside a Faraday cage with minimal accelerator-related wiring outside it. We had also decide to ‘do it properly’, having had past experience with home-brew designs, which did work, but which inevitably looked messy. Rainford EMC (http://www.rainfordemc.com/contact-us.html) came to our rescue and supplied us with a customized enclosure at reasonable cost.

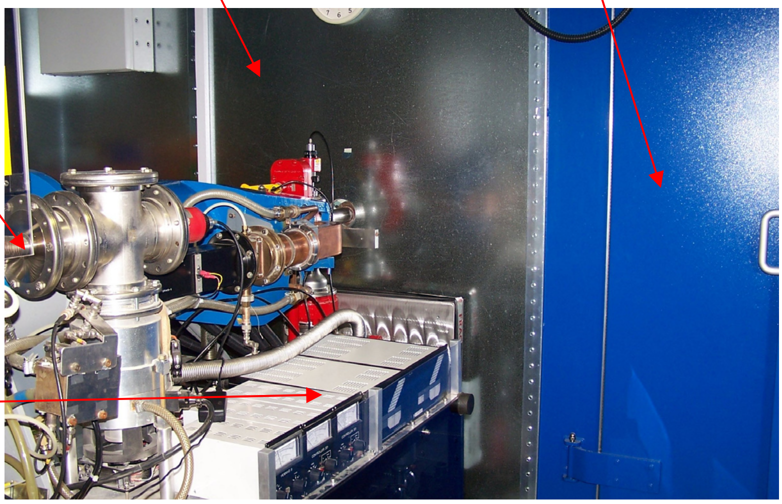


The linear accelerator vault and details of the Faraday cage.

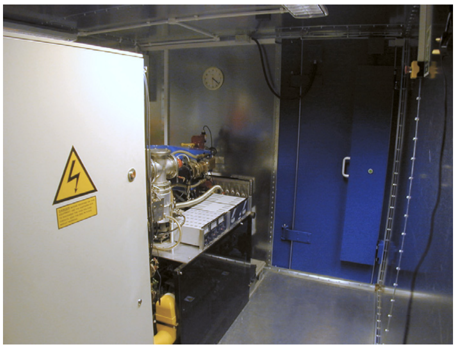
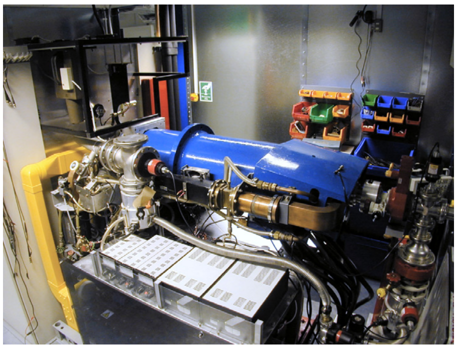
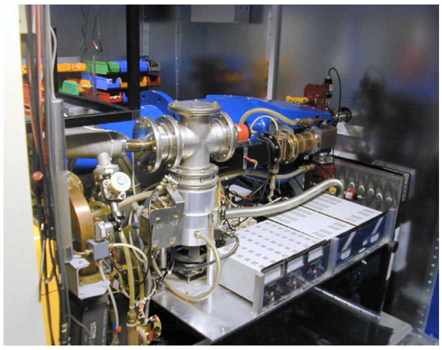


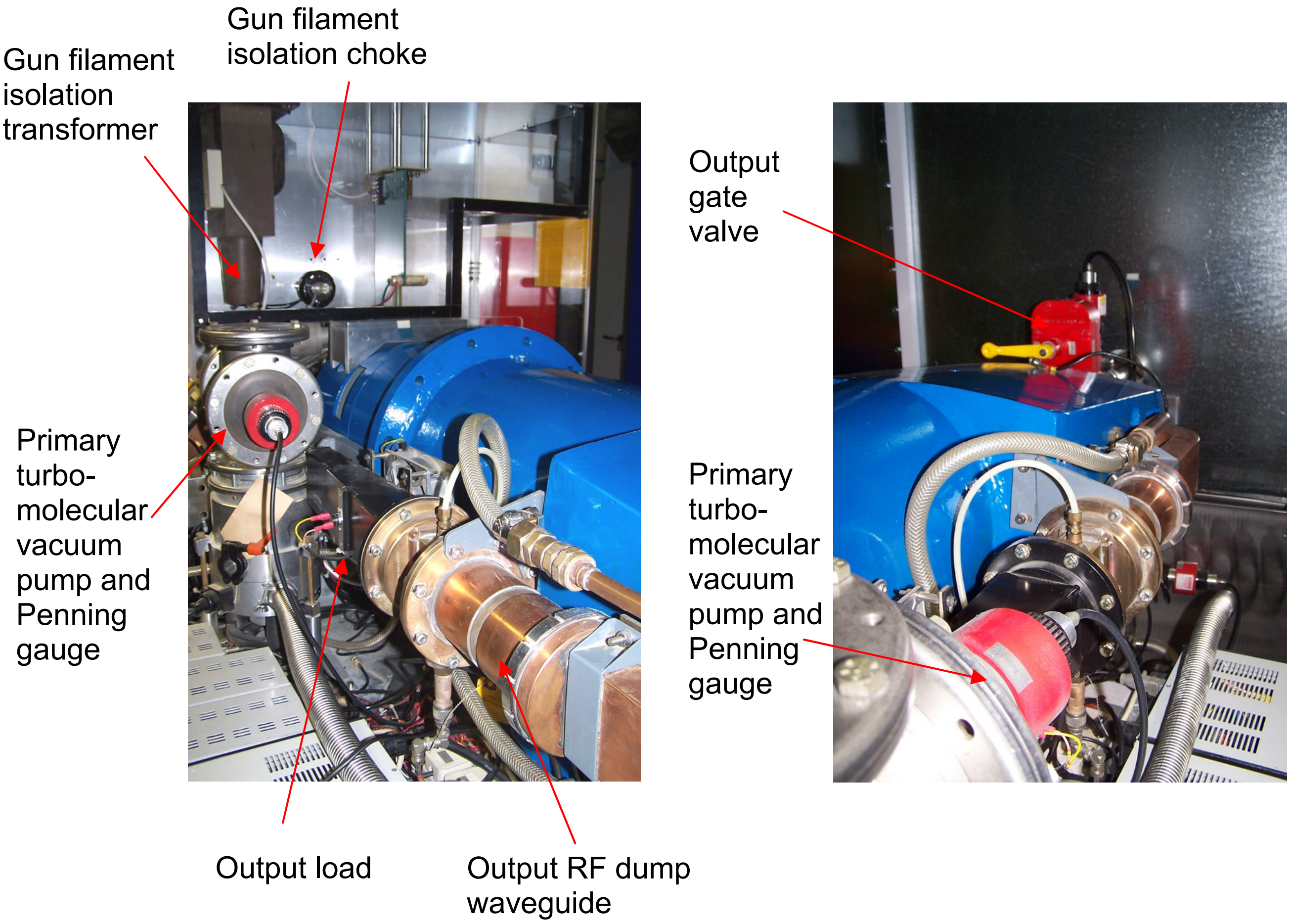
The installation of the linac coincided with the move of the Group to the Institute of Radiation Oncology and Biology. In other words we were involved in numerous projects at that time and it is no surprise that a cartoon made its way to the linac area:



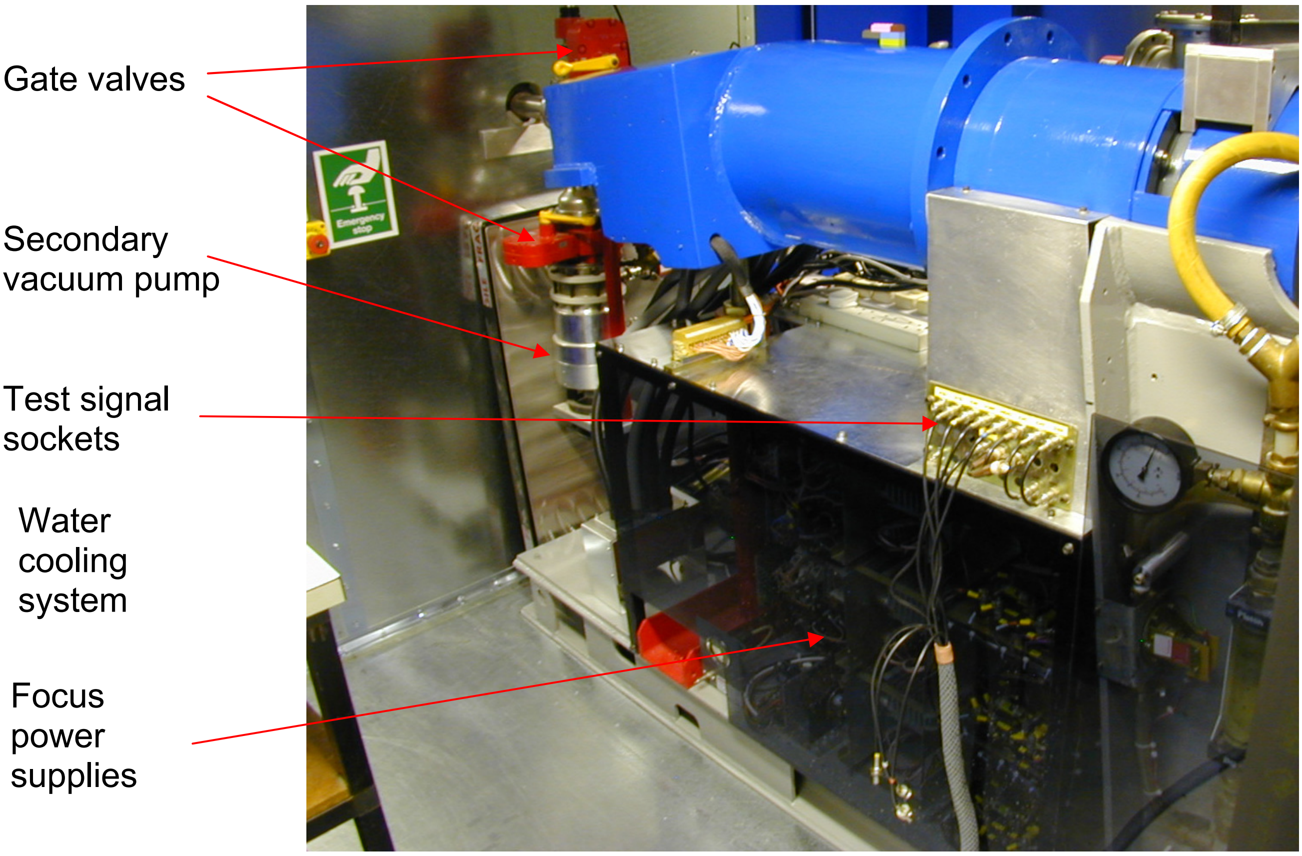


Nevertheless, the accelerator was installed within the Faraday cage (in the right position!), at which point it became increasingly hard to keep photographic records, as can be seen from the following images.

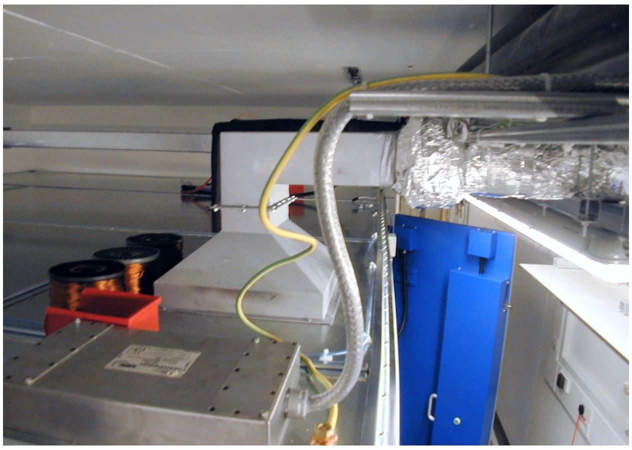






Two views of right-hand side of accelerator (above) and of the left hand side.

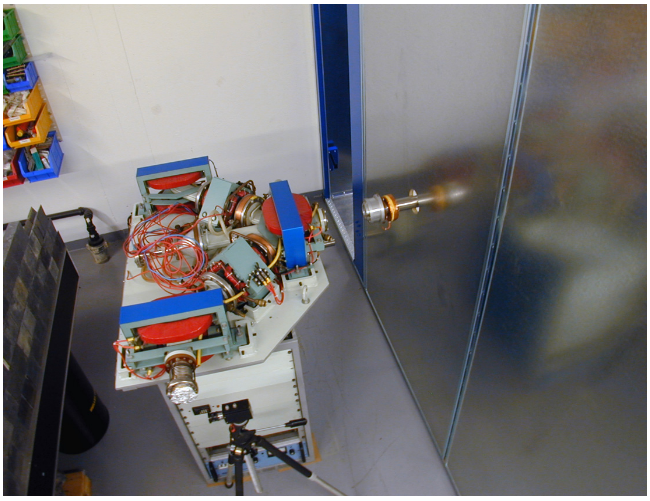


The outside of the cage was boringly neat and shiny. We had provided two entrance doors, one at the side of the cage, the other at the beam end of the installation, as shown below.



The beam end of the Faraday cage (top left), soon to be covered by a shielding wall, the side entrance (top right) and the cage ceiling, showing how ventilation ducts and three-phase power input cables interface to the cage. The power is filtered with custom RFI filters (C, L, C ‘PI’) on all lines.

The only electrical connections to the cage are the power input and low voltage radiation safety interlock cables, also filtered through custom PI filters. All other connections are via fibre-optic cables, two if which carry USB2.0 signals.



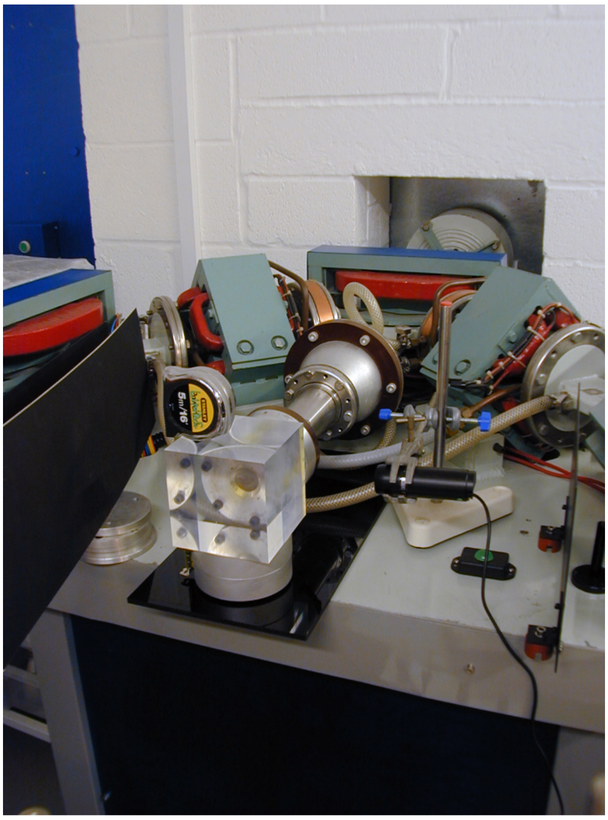
The immediate area outside of the beam end of the Faraday cage is dedicated to a beam switching magnet system. The rack below this is dedicated to DC magnet power supplies.

As soon as the Faraday cage was completed, an additional shielding wall was constructed from high density concrete blocks. This potentially messy process was completed in around one week by a tem of expert builders ‘found’ by the Institute’s building manager. We could only watch with amazement how the heavy concrete blocks were expertly put into place as if they were made of polystyrene!

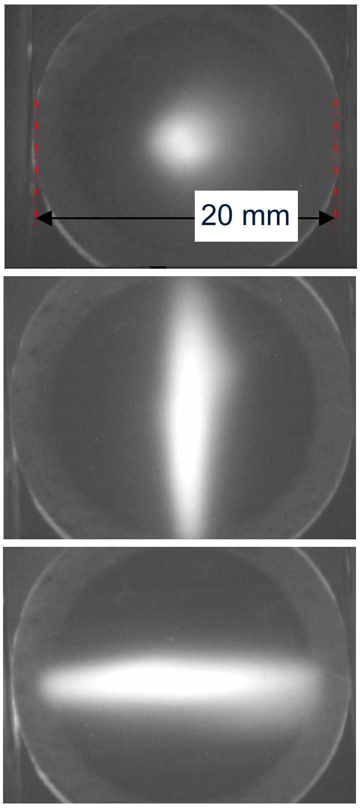
Covering the beam line end of the Faraday cage with staggered, offset blocks.

This type of construction ensures minimal radiation leakage consequences due to potential ‘gaps’ in the block-work.

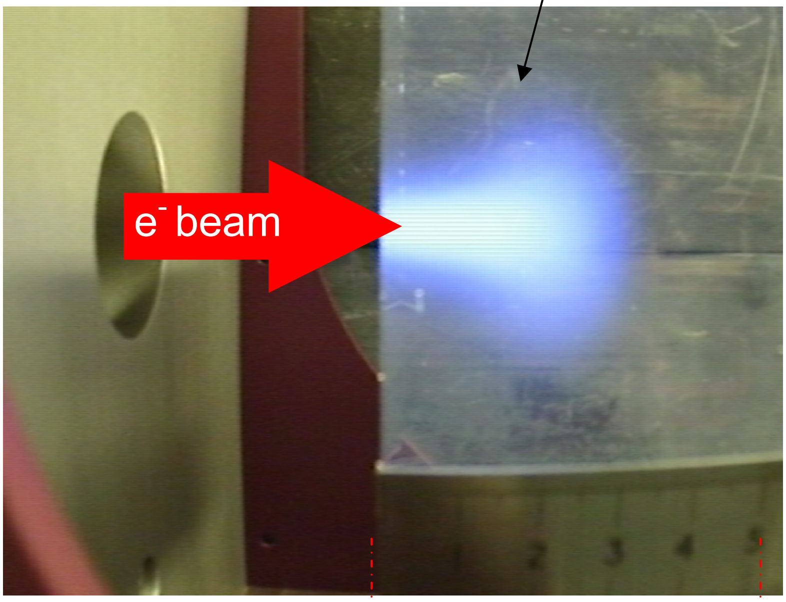
A somewhat challenging task was to carefully place a concrete lintel above the beam output focus solenoid magnet. It was not really necessary to do it that way: we could have dismantled the vacuum system. We just pretended that we needed everything to fit precisely rather than to admit to a certain degree of laziness in vacuum system dismantling!



So now we had a neat Faraday cage enclosure with an accelerator inside it and a beam switching system outside the freshly painted shielding wall. We placed a scintillator block at the end of the beam line (right image) and turned everything on, hoping that it would work as expected. In reality of course, we had turned on the machine for test runs before all the building work and were confident that it would indeed work! But when all was adjusted properly, everything worked just fine and we could see and manipulate the beam, as shown below.



Beam shape control with quadrupole magnets

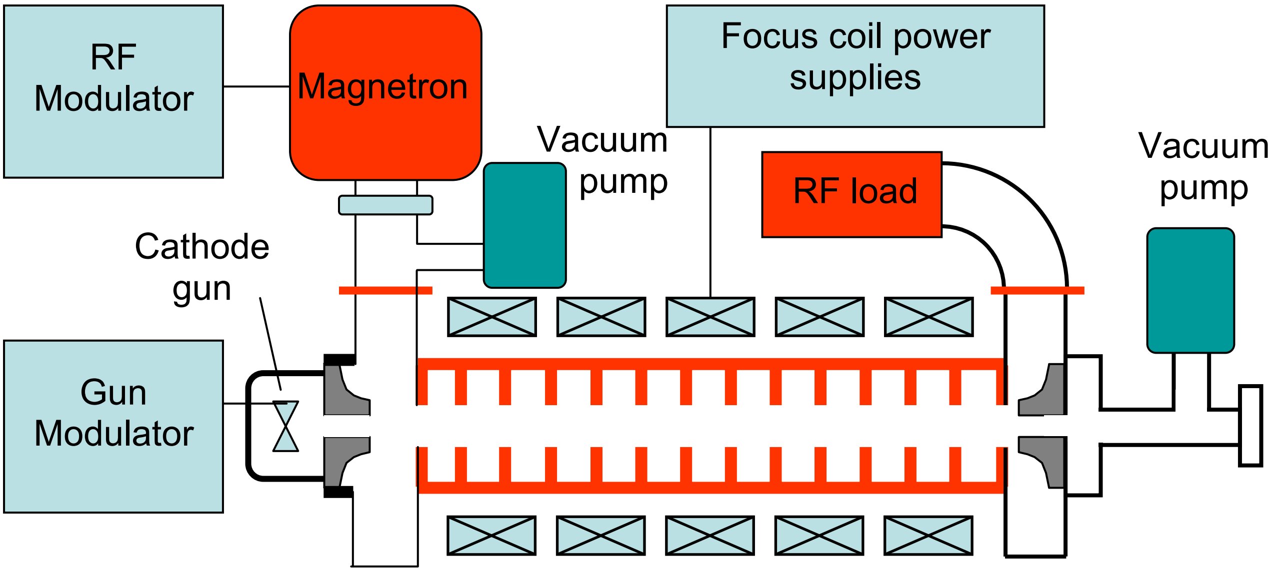


Electron beam luminescence in solid scintillator

In the meantime, work outside the accelerator area had been going on. The extensive software system, described separately, had been coerced into life by Stuart Gilchrist, shelves and monitors installed and finally, in late 2009 we were at the stage of having an installation which was very close to what was conceived earlier.

Clearly it all worked as expected, as can be seen from Stuart Gilchrist's relaxed pose in the image below on the left. Things were not always as relaxed as this, as can be seen in the image below on the right!

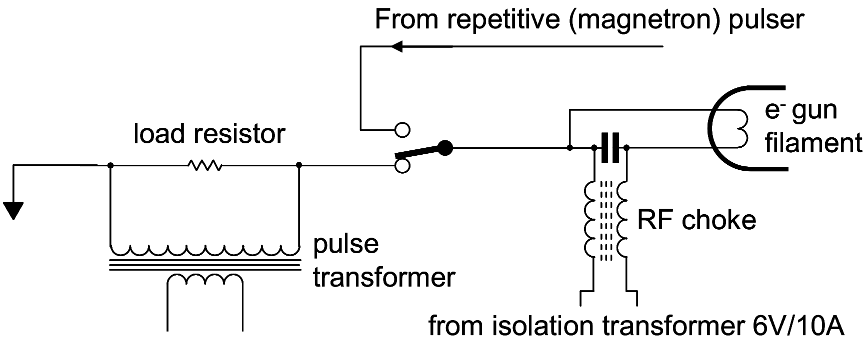
It is useful at this point to remind the reader about the basics of electron linear accelerator operation. Electrons are generated in a thermionic cathode and accelerated to ~40-50 kV before injection into the acceleration cavities (the waveguide), supplied with radiofrequency power (3 GHz in our case) generated by a high power (2 MW) magnetron, driven by a pulsed modulator. Normally, this modulator delivers a pulse of several microseconds and this pulse is also used to inject electrons at the appropriate energy into the waveguide system. The beam is prevented from colliding with the edges of the cavities by a strong focusing magnetic field generated by a series of coils around the waveguide, supplied by several focus power supplies. Unused radiofrequency power is dumped into a load and the waveguide is kept under vacuum.

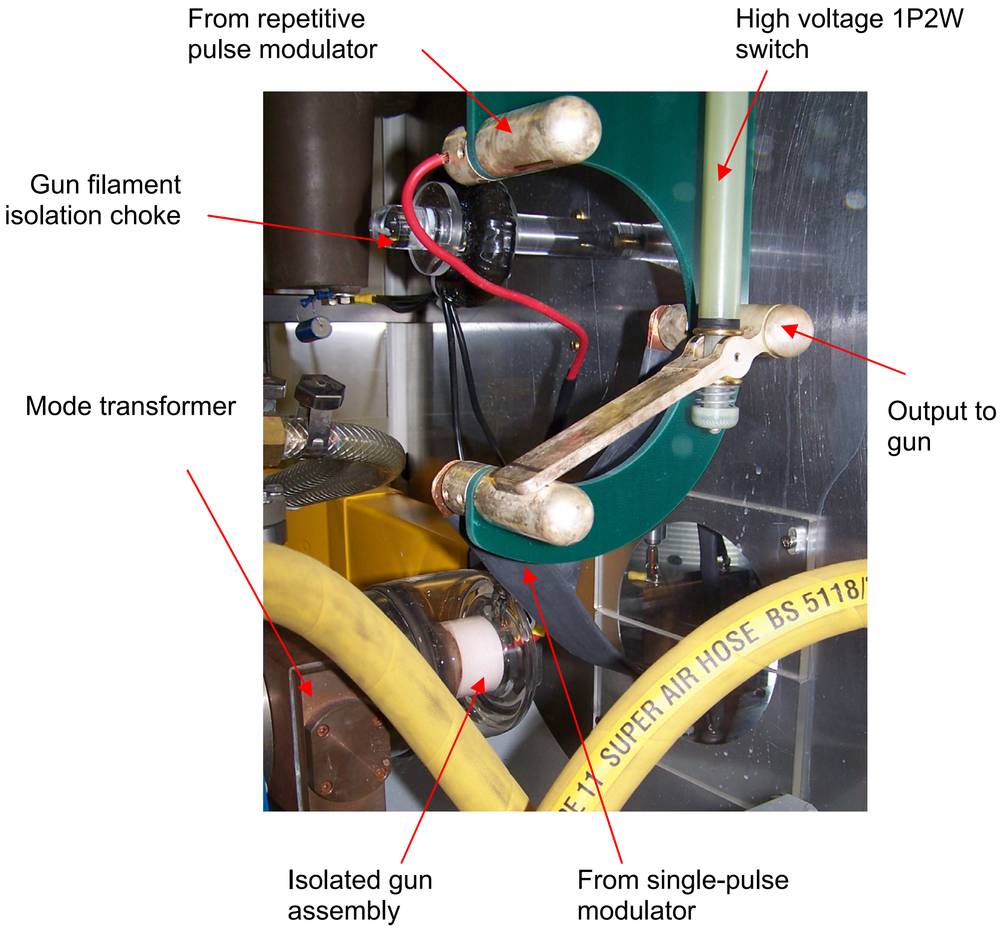


One of the features of our linac is that it is capable of producing single, variable width pulses on demand, in addition to the more usual repetitive pulses of ~4 μs. We achieve this by using a separate gun modulator. This is synchronized to the RF modulator and delivers a pulse to accelerate injected electrons during the much longer microwave pulse.

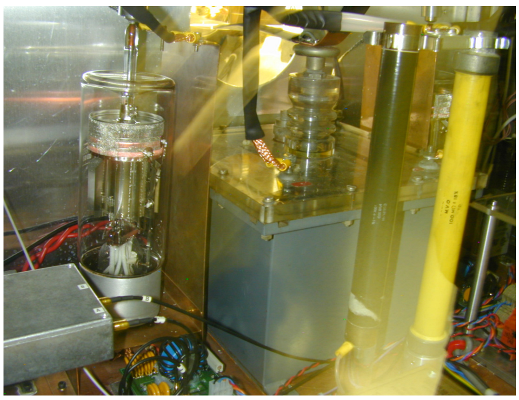
The peak current of the injected charge pulse (and hence the output pulse) is determined primarily by the thermionic cathode temperature. The cathode is thus driven with a variable current, but must be isolated from ground, as its potential is raised to several tens of kilovolts.

The arrangement used to generate these short pulses (~50 ns – 1 μs) is shown below. We use a changeover switch to select between the usual repetitive pulses and the pulses delivered by the gun modulator. This switch must obviously also be isolated from ground potential and is shown in the image below.

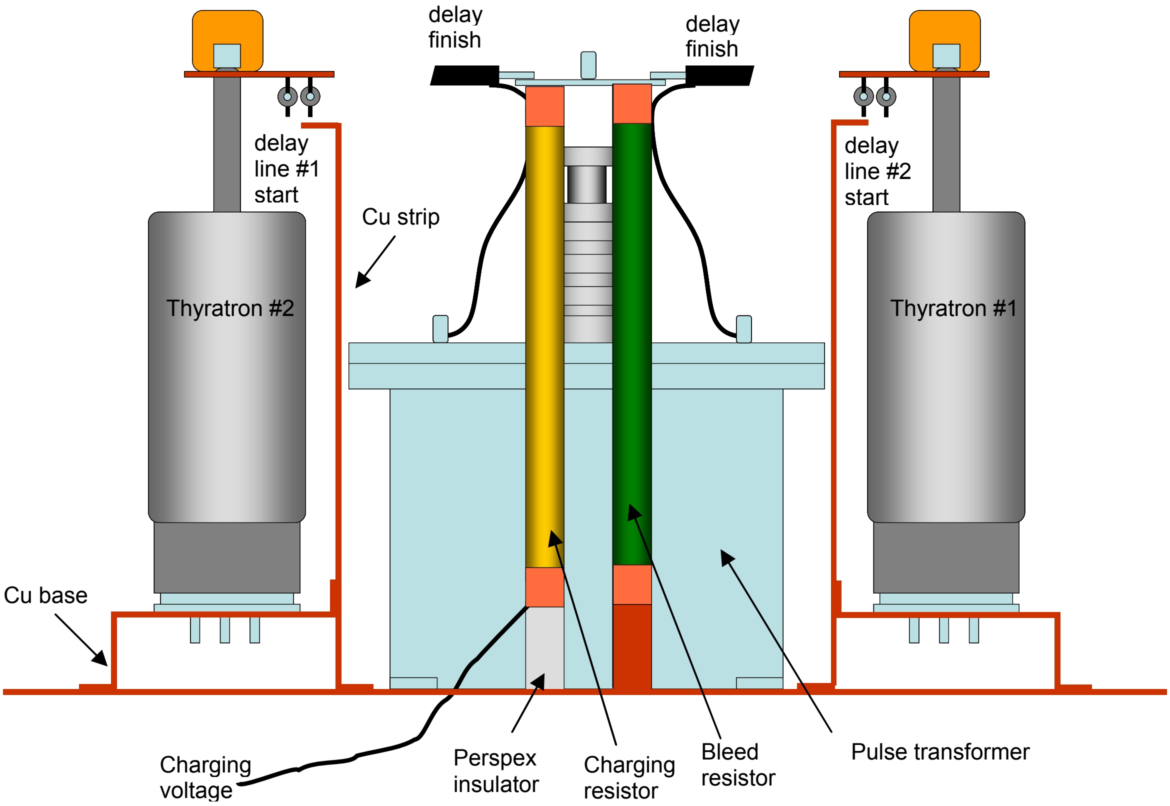


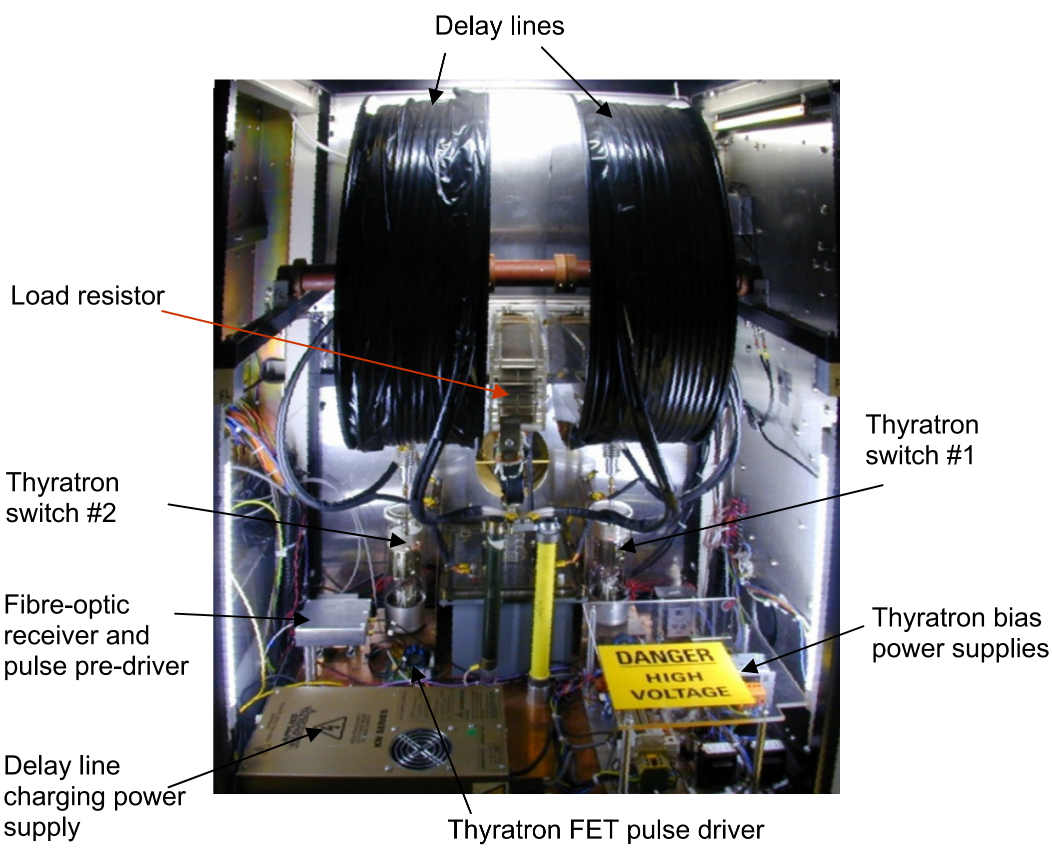


The gun modulator is based around somewhat dated, but effective thyratron switches (shown on the right); we had acquired several such switches over the years, and this approach was thus extremely cost-effective. Similarly, the output pulse transformer was ‘to hand’ and we were thus able to develop a novel type pulse generator to deliver many tens of kV at variable pulse widths.

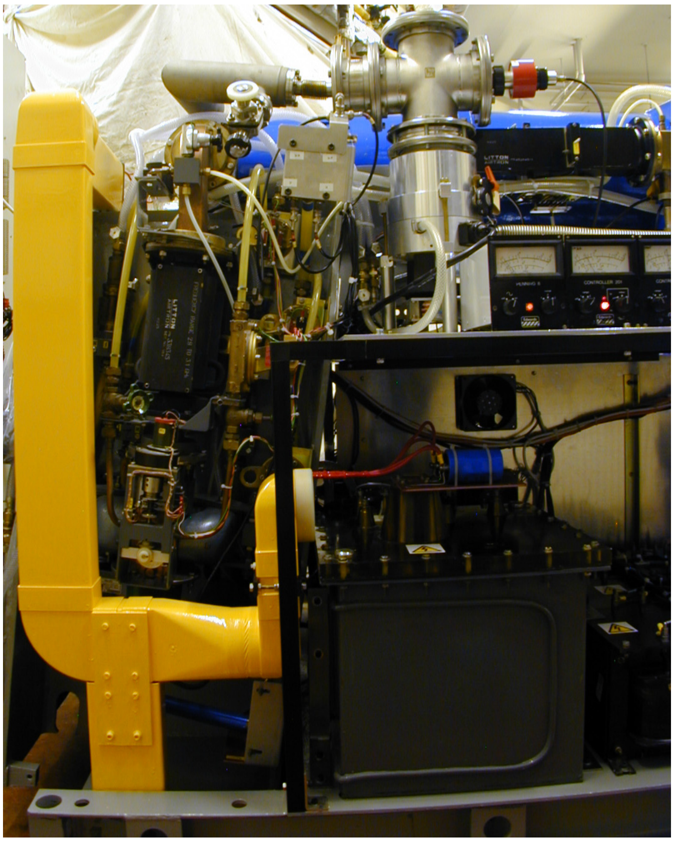


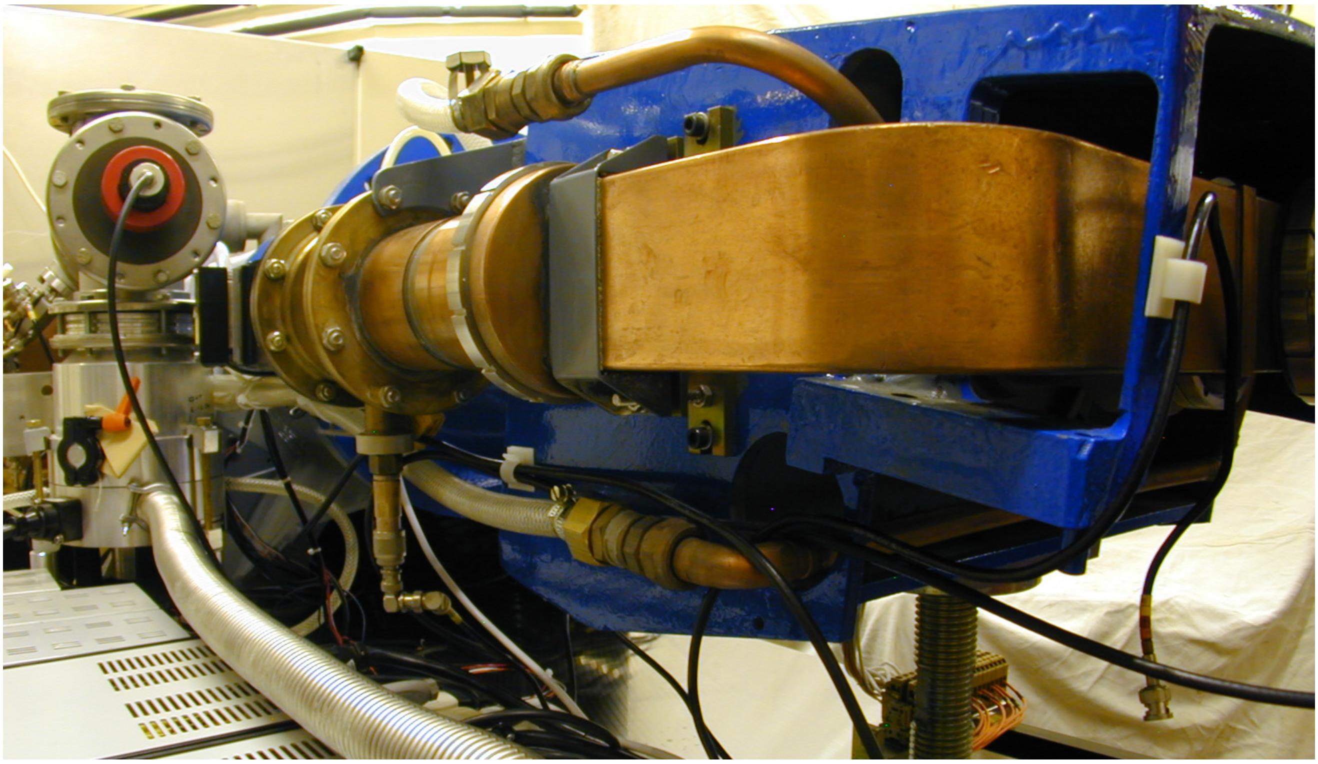
The construction of the delay-line based single pulse modulator is shown below. It operation will be described separately. The practical realization is shown in accompanying image at the bottom of the page.





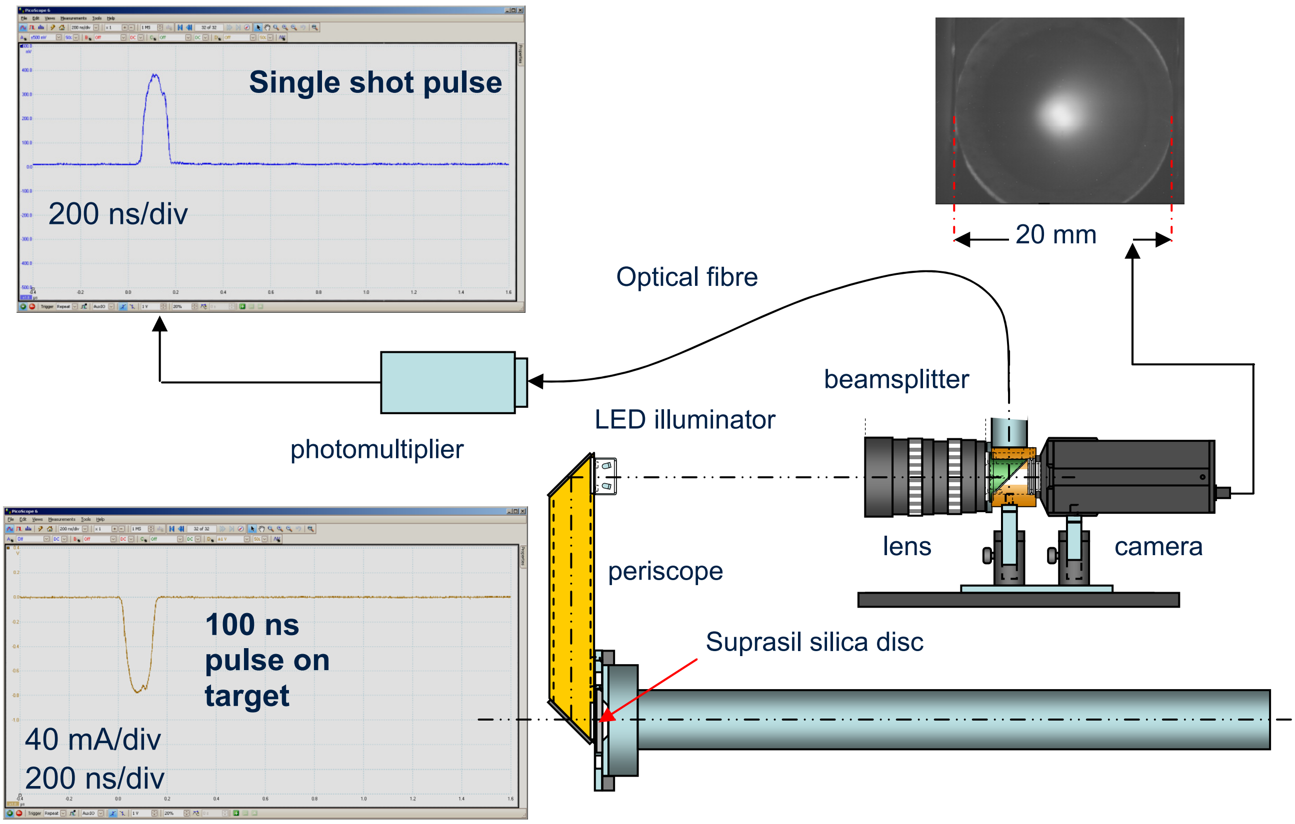
The machine's original magnetron modulator was not tampered with, other than relocating the main output pulse transformer. Its high voltage output pulse was guided to the magnetron and to the gun switch within insulated trunking (actually plastic trunking intended for bathroom ventilation systems!). Images of the radiofrequency source and the microwave output load are shown below.





The linac's control system was extensively modified and matched with a new control software system. These will be described separately. However, we had decided early on in the project to provide convenient monitoring of the pulsed beam, both of its spatial position and of its temporal profile. This is achieved by placing a thin (~1-2 mm) Suprasil silica disc at the output of the beam.

Čerenkov light generated by the electron pulse travelling through the disc is reflected by a pair of mirrors ('the periscope'). This is fashioned from a stainless steel polished mirror (ladies vanity mirror!) closest to the beam, used as it is able to dissipate significant pulse-generated heat and a conventional first-surface mirror. Several LEDs are placed close this second mirror and are appropriately angled so as to illuminate the output window and silica disc. The Čerenkov light is sampled by a telephoto lens intended for 35 mm film operation. Such lenses can be obtained at very low cost, now that 35 mm film is going out of fashion. The advantage of such a a lens is that its back focal distance is large, allowing the placement of a beam splitter ahead of a CS-mount CCD camera. Most of the light goes through to the CCD, but around 20% is reflected onto a short focal length lens which guides it onto a 1 mm diameter polymer fibre. This fibre is coupled to a miniature photomultiplier tube and allows monitoring of the temporal pulse profile.

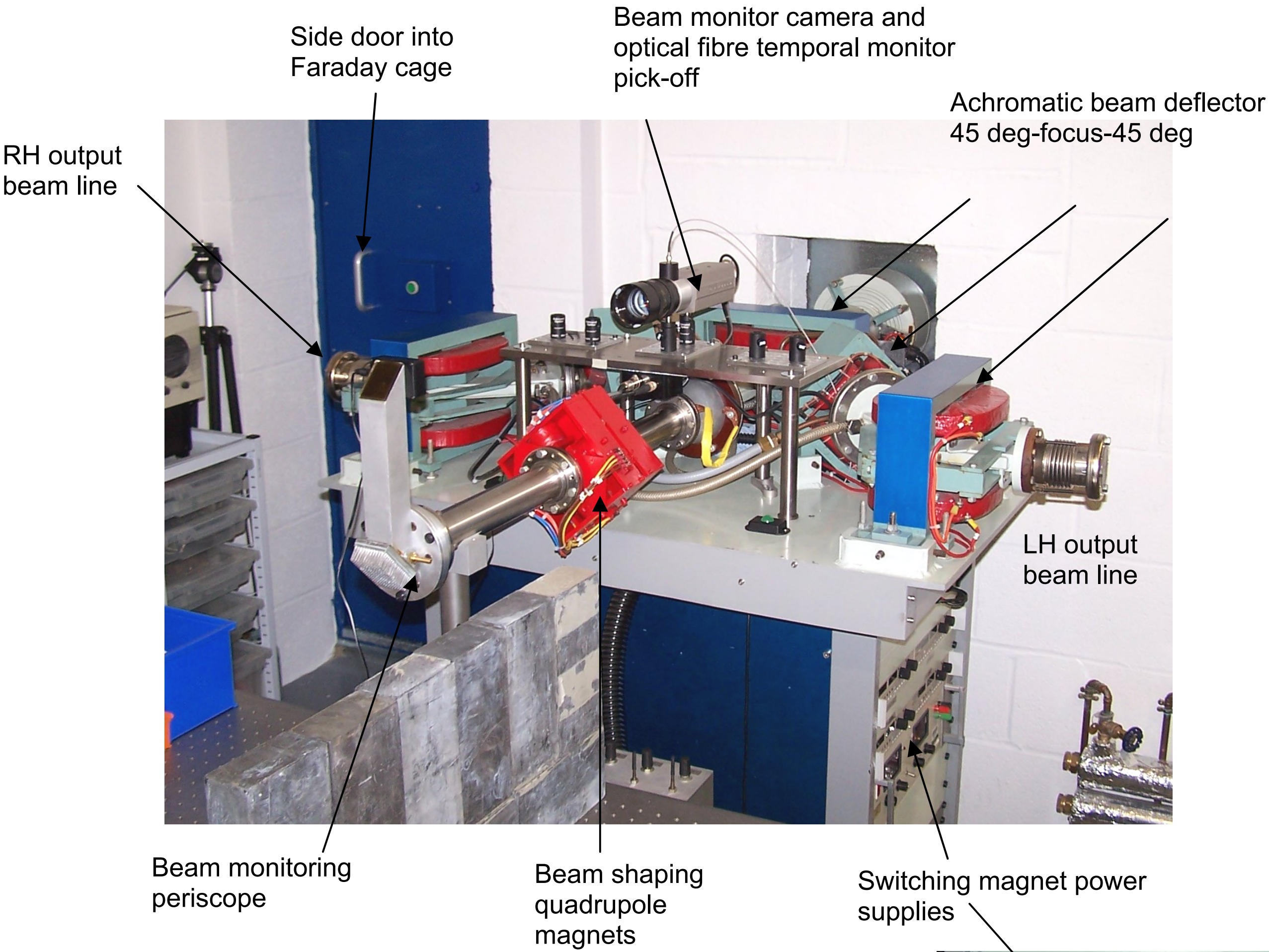


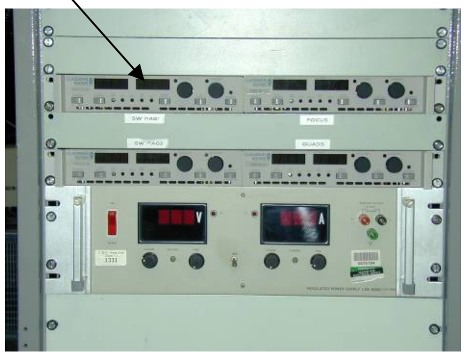
The lens/camera/beamsplitter can be rotated through +/- 90 degrees and the 'outputs' of any of the three beam lines can thus be monitored.

We use the venerable Cohu 4900 series camera which can operate in a triggered integration mode. The exposure of the camera can thus be synchronized to the beam pulse and the resulting image can be captured using a frame grabber. We are grateful to Brian Reece Scientific (BRSL Ltd, http://www.brsl.co.uk/) for supplying us with a stand-alone frame grabber.

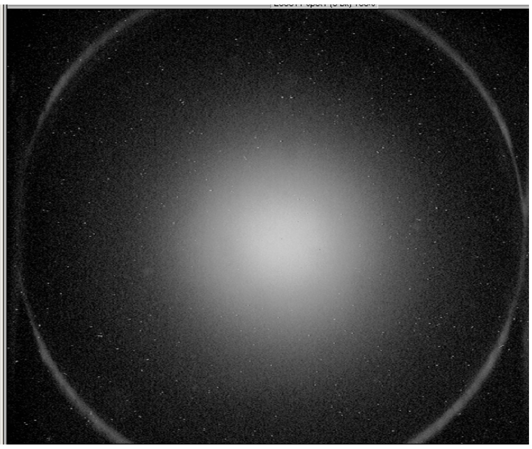
We have not mentioned the beam deflection system before. This is yet another 'acquired' system. It was originally designed by High Voltage Engineering Corporation for use with the 'old' Gray Institute Van de Graaff accelerator, taken out of service in mid 2006. A few leaks were expertly fixed by the Mechanical Workshop, and after thorough cleaning and a bit of rewiring we had saved many thousands of pounds!

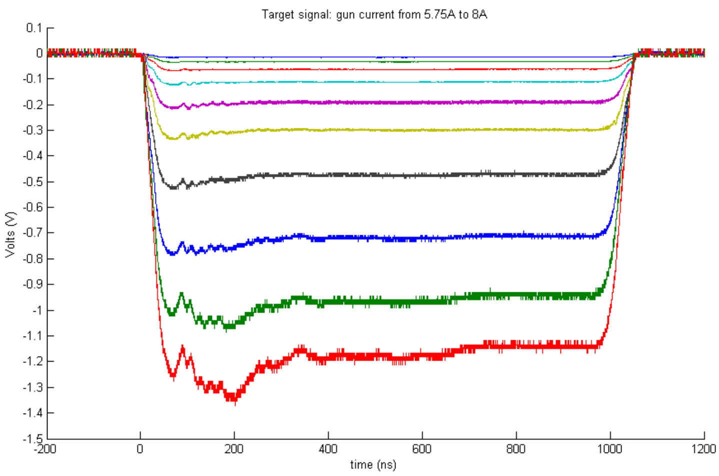
The final beam shaping quadrupole was originally constructed by Jack Boag and Barry Michael at the Gray in Northwood. We had kept it as it 'may be useful one day'. We gave it a coat of paint and it was!





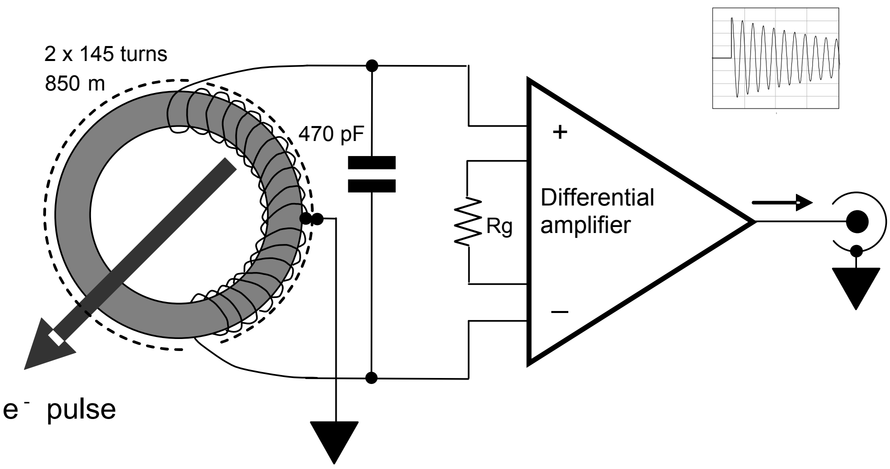
The beam deflection magnets and the beam monitoring system.



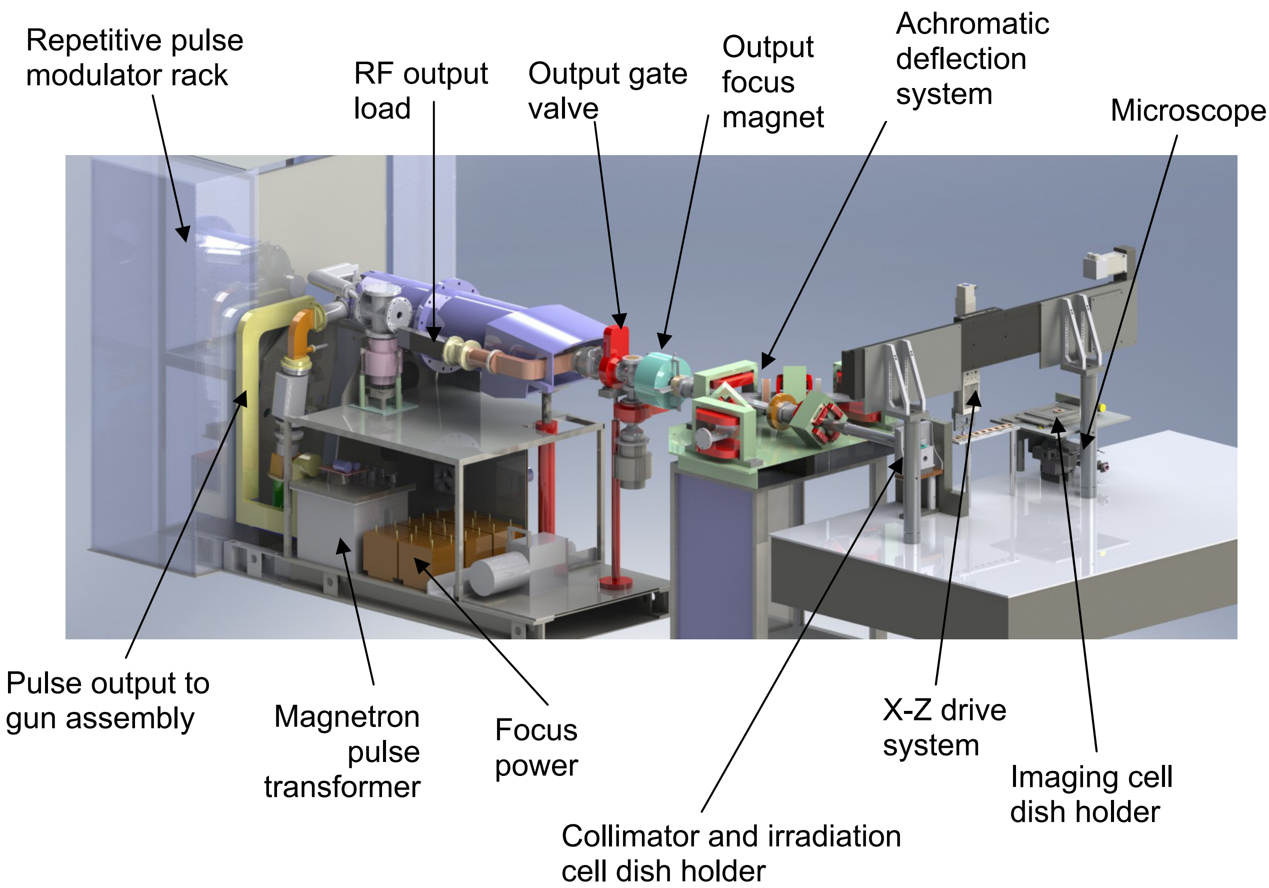


Such a beam monitoring arrangement is just fine when performing beam alignment prior to an experiment. However, when the periscope is removed, the operator would be 'blind' to the delivered pulse. To overcome this, a beam charge monitor is placed in the accelerator output beam line.

Here we use a large ferrite core around the beam line and wind this with a layer of copper wire. The arrangement thus behaves as a transformer, with the beam acting as a single-turn primary. The output is arranged as tuned circuit which resonates when the beam pulse traverses the core. The resulting oscillation decays over a few milliseconds and the resulting amplitude of the 'ring' is proportional to beam pulse charge. A differential arrangement makes the system insensitive to external electric and magnetic fields. Details of this will be described separately.



The accelerator facility was thus completed in late 2010. All we now had to do was to develop the experiment facility. By now Iain Tullis had become very proficient at drawing in SolidWorks and this final 'addition' was thus easy to draw in as part of the overall assembly, as shown below. This arrangement is described separately.



This note was prepared by B. Vojnovic in late 2011. Many people have contributed to the successful installation of the linear accelerator but the bulk of the work was undertaken by Iain DC Tulis, Robert G Newman, John Prentice and Gerald Shortland, while Paul R Barber and Glenn Pierce helped out when software became too difficult. We are grateful to a number of people associated with the Institute building and Oxford Estates in the early phases of linac facility design.

We acknowledge the financial support of Cancer Research UK, the MRC and EPSRC.