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A DIAGNOSTIC TEST BENCH FOR THE LIGHT ACCELERATOR

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Abstract

The LIGHT accelerator is a compact Linac that will deliver proton beams of 70 to 230 MeV for cancer treatment. The LIGHT prototype is currently being commissioned by AVO / ADAM at CERN. Here we present the design and implementation of a moveable diagnostic test bench which is used to measure the beam properties at each commissioning step. Parameters measured include beam current, pulse length, energy, position, transverse profile and emittance.

The first results obtained with the low-energy test bench for beams up to 7.5 MeV are shown here. We demonstrate that the instrumentation used achieves a very high sensitivity, dynamic range, reliability and immunity to EM noise. Procedures for on-line calibration of the instruments are also discussed.

INTRODUCTION

LIGHT consists of a sequence of accelerating modules of different kinds. The beam is generated in a proton source, which produces a DC beam at 40 keV. Following this is a chopper that selects a beam pulse of as little as 0.5 µs and then an RFQ operating at 750 MHz, in which the beam is bunched and accelerated to 5 MeV. There are then four Side-Coupled Drift Tube linac (SCDTL) modules, operating at 3 GHz. Each module consists of a number of accelerating cells and increases the energy of the beam by a few MeV. Finally there are 15 Coupled Cavity Linac (CCL) modules, each again consisting of a number of cells, which bring the beam to its final energy of 230 MeV. The LIGHT prototype, currently under construction at CERN, will include only the first of these CCL modules and will therefore reach a lower energy.

For the commissioning of the LIGHT prototype, each of these modules is being installed individually in sequence, in order to allow the evolution of the beam parameters down the linac to be characterised with as much detail as possible. For subsequent LIGHT installations, a step-wise approach will be used, installing several modules together in order to reduce the commissioning time while maintaining the ability to measure key parameters and establish set-points.

The full LIGHT accelerator will include beam diagnostics between some modules and in the beam transfer line between the accelerator and the treatment room. However, these will not allow the beam to be fully characterised at all locations. During the commissioning stages a more in-depth measurement is required, and with this in mind 3 diagnostic test benches have been designed. As each module is added, the test bench is placed at its output. Because of the change in beam parameters along the linac, a single test bench cannot be used in all locations. Instead, three variations are used: the first to measure the proton source output; the second from the end of the RFQ until the last SCDTL module, and the third for the CCL modules.

SOURCE TEST BENCH

The beam exiting the proton injector is highly divergent and the source test bench must therefore be kept as short as possible. It consists only of two Diagnostic Boxes (DBox) and an in-line Faraday cup which doubles as the beam dump. The DBoxes are based on a compact design used at CERN's HIE-ISOLDE accelerator and contain two insertable arms, one a blade with two orthogonal slits in it and the other a moveable Faraday cup [1].

Scanning one of these slits through the beam while measuring the transmitted current on the Faraday cup measures the beam profile. Scanning both slits while measuring the current on the Faraday cup of the second DBox samples the beam phase space and allows the emittance and Twiss parameters to be computed [2]. For any position of the two slits, the first produces a cut in position, while the second produces a cut in angle dependent on the difference in the position of the two slits divided by the distance between them. The distance from the first to the second slit is 200 mm and the slit width is 0.2 mm, which means that the phase space can be sampled with a resolution of 0.2mm and 1 mrad. Because of this double cut on the beam, only a small fraction reached the Faraday cup, which therefore must be sensitive down to the level of a few nA.

Each blade contains two slits, one horizontal and one vertical, with a sufficient separation so that the beam never passes through both slits at the same time, and the blade itself is inserted at 45 degrees. Thus, both the horizontal and vertical emittances can be measured with this setup. This arrangement, together with an extremely compact Faraday cup design, allows the flange-to-flange length of the whole DBox to be kept down to 58 mm. The insertable arms are moved using stepper motors, and the repeatability of the whole system is at the level of a few µm.

RFQ AND SCDTL TEST BENCH

The DBoxes described above are also used in the test bench used to measure the beam from the exit of the RFQ up to an energy of 37.5 MeV. The only change is that, since the beam's geometric emittance is much smaller than after the proton source, the distance between the two DBoxes is increased to 800 mm with a consequent reduction in the angular resolution of the phase space measurement down to 250 µrad and the slit width of the first DBox is reduced to 100 µm.

The impact of the finite slit widths on the reconstructed emittance has been analysed for slit openings from 50um to 400um in a step of 10um. For each combination of slit

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openings, the measurement was simulated using the expected beam and a 5 nA cut-off in the Faraday cup, and the Twiss parameters reconstructed from this virtual measurement are compared to the expected beam. When the slit widths are too small, the resolution is in fact worse because very little current reaches the Faraday cup. For the chosen widths of 100 and 200 µm in DBox 1 and 2 respectively, we expect an error of 0.4% in emittance, 4% in Twiss α and 2.5% in Twiss β.

In addition to the DBoxes and the end Faraday cup, this test bench will also include two Beam Position Monitors, three phase probes, a spectrometer and a scintillating screen.

The Beam Position Monitors (BPM) consist of a circular electrode, 20 mm aperture and 15 mm length, divided into four segments each with 60 degrees of coverage. The 750MHz signal induced on each electrode is amplified using a broadband amplifier located close to the BPM. The four signals are then acquired and processed using a Libera Spark HL unit [3]. This unit includes remotely settable attenuators on each channel, which can be used to adapt the readout across the full intensity range. The Spark unit is placed directly under the BPM, keeping the signal path as short as possible. Nonetheless, interference from the RF system is problematic and limits the sensitivity of the BPMs in the lowest beam current range.

The phase probes are used to calculate the beam's time of flight and thus the mean energy of the beam. They are of the same form as the BPM except that the electrode is not split into segments. Their output is connected to a specialised acquisition system that is described in a separate contribution [4].

After passing through the other test bench instruments, the beam enters a dipole magnet which is used as a spectrometer. The spectrometer arm is at an angle of 18 degrees to the accelerator axis and ends in an end Faraday cup identical to that on the straight line. The spectrometer is used as a cross-check of the energy measured by the time-of-flight system and to measure the energy distribution of the beam. A moveable slit in front of this Faraday cup allows the beam profile to be measured. Due to the dispersion in the spectrometer arm, the horizontal profile contains information on the beam energy spread. To increase the accuracy of the energy spread determination, two electromagnetic quadrupoles located on the test bench are used to minimise the horizontal beta function at the position of the slit.

The scintillating screen consists of a YAG:Ce plate arranged at 45 degrees to the beam path on an insertable arm. The screen is 100 µm thick and has a diameter of 25 mm. A simple CCD camera observes the screen through a fused silica viewport. The scintillating screen is not intended to provide quantitative profile data but rather as a quick visual check of the beam condition. It has also proved very useful in setting up the quadrupoles and as a check of beam stability.

The test bench layout is shown in Figure 1. The length of the whole bench including the spectrometer is approximately 4 m.

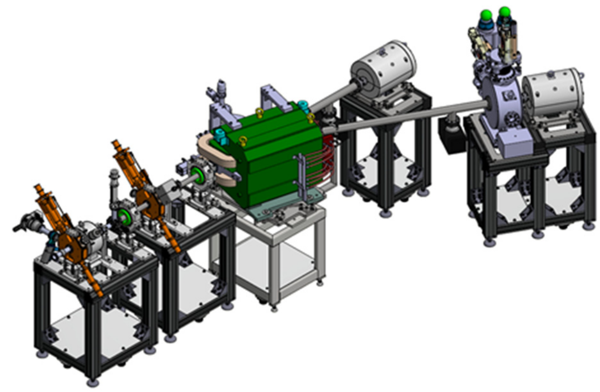

Figure 1. Layout of the RFQ/SCDTL test bench. Beam enters from the left. The DBoxes, BPMs, Phase Probes, EM quadrupoles, spectrometer dipole and end Faraday cups are shown.

HIGH-ENERGY TEST BENCH

Above 37.5 MeV, the blade of the DBox is no longer sufficient to stop protons. In addition, stopping the beam on the small moveable Faraday cups would cause a high level of activation, compared to the use of a larger fixed beam dump that can be adequately shielded. Therefore, the DBoxes will not be used in the high-energy test bench.

As an alternative to the DBox for profile measurement, a Fiber Scanning Monitor (FSM) will be used. The FSM consists of two insertable arms, one horizontal and one vertical. Each arm has a scintillating fiber held in a fork such that it can be scanned through the beam path. The fiber is coupled to photo-multiplier tube located on the outside of the vacuum chamber. The fiber has a square profile with 250 µm side. The light yield is expected to be more than sufficient and a small neutral density filter can be placed between the end of the fiber and the PMT module to prevent the latter saturating. The full intensity range of LIGHT can be covered by varying the bias voltage and thus gain of the PMT. The FSM was designed at CNAO based on the Watchdog detector in use there [5].

Instead of the two-slit method, a quadrupole scan technique will be used to reconstruct the transverse emittance [6]. The relatively low beam current and consequent lack of space-charge effects at LIGHT mean that it should be possible to accurately extract the emittance from the quad scan results using a simple analytical approach. The same setup will also be used for phase-space tomography in which the full phase space is reconstructed. However, chromatic effects will have to be taken into account at certain intermediate beam energies where the energy spread is considerable [7].

The BPMs, current transformers and phase probes described in the previous section will continue to be used in the high-energy test bench. In the full LIGHT installation, a spectrometer will also be present at all energies. In the prototype installation however, space constraints will not allow the use of the spectrometer above 37.5 MeV. The beam energy will be measured instead using a Multi-Layer Faraday Cup adapted to measure low energy beams [8].

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MEASUREMENTS

The source test bench was used for measurements between August and December 2016 and the RFQ/SCDTL test bench has been in use since February 2017, first placed after the RFQ and then after the SCDTL1. We present here some examples of the measurements taken, in order to illustrate the capabilities of the test benches. Other results showcasing the accelerator performance are presented in [9] and [10].

Figure 2 shows an acquisition of a single beam pulse using one of the insertable Faraday cups. It can be seen that the noise level of the instrument is extremely low. The sampling rate of the ADC is 50 MS/s although the analogue bandwidth is somewhat lower. Since the Faraday cup is the basis for the profile and emittance measurements, this allows slice emittance measurements to be performed. Profile measurements taken with the two DBoxes are shown in Fig. 3. The size increase between the two DBoxes, 80 cm apart, is expected since there are no focusing elements on the test bench. The two electromagnetic quadrupoles on the test bench are used only for spectrometer measurements. Finally, emittance measurements are shown in Fig. 4. Such a scan takes around 10 minutes per plane; higher resolution scans can be performed with an increase in measurement time proportional to the number of points measured. An arbitrary phase-space area can be scanned. Defining an area that encompasses the expected beam at that location, with some margin,

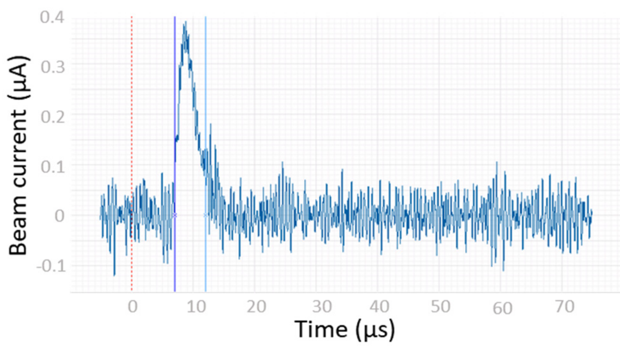

Figure 2. Faraday cup measurement of weak (~400 nA) beam, taken with the highest gain setting and illustrating the extremely low noise and high time resolution. The red vertical line represents the trigger for the BD acquisition crate, the two blue vertical lines are a selectable integration window used by the profile and emittance procedures.

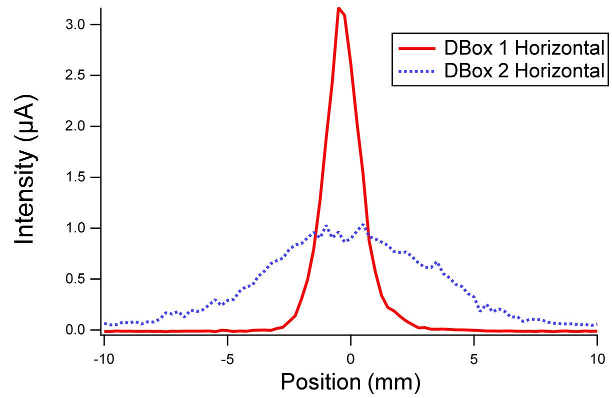

Figure 3. Horizontal beam profiles taken at the two DBoxes of the test bench placed after the SCDTL1.

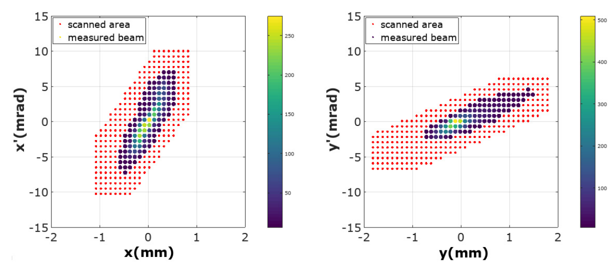

Figure 4. Transverse phase space of the 5 MeV beam, measured by the two DBoxes of the test bench. Horizontal plane on left, vertical plane on right. Red points show the measured phase space area; colour map shows the points with measured beam above 5 nA.

CONCLUSION

We present the design and example results of the diagnostic test benches used in commissioning the LIGHT accelerator. The test benches allow a thorough characterization of the beam produced at each accelerating module. The instruments and acquisition system are adapted to the low intensity, high dynamic range and pulse-to-pulse variation of the LIGHT accelerator. They include self-calibration systems where possible in order to allow an online check of the system performance. The test benches have been used for the commissioning of LIGHT up to 7.5 MeV and are now ready for beam at 16 MeV.

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