Development of a Beam Loss Detection System for the CLIC Test Facility 3

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Abstract

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INTRODUCTION

A new test facility, named CTF3 [1], is under construction at CERN with the aim of demonstrating the feasibility of the Compact Linear Collider (CLIC) [2], as a high luminosity, 3TeV center of mass energy e^+e^- Collider. The CTF3 linac is composed of 18 consecutive fully loaded 3GHz cavities which will accelerate a 3.5A, 1.6 μ s long electron beam pulse up to a final energy of 150MeV. Housed in the LEP injector tunnel, the linac is scheduled for completion by the end of 2004. The installation has started in January 2003. The injector, including the 3GHz bunching system and two accelerating cavities, has already delivered 20MeV electrons in July 2003. Two extra cavities have been installed during the rest of the summer and commissioned toward the end of the year.

Northwestern university is currently developing the beam loss detection system for the CTF3 linac. Thermal calculations have shown that losses are dangerous only if they exceed 10% of the total beam current. This means that the machine protection system can be based on wall current monitors [3]. Beam losses are measured and minimized in order to keep the radiation level and the activation as low as possible all along the linac. It is however important to remind that for the CLIC Drive beam linac beam losses would have to be measured with an accuracy which is not achievable with wall current monitors. And the development of beam loss monitor on CTF3 must be pursued with the aim of acquiring the required technology relevant for CLIC.

Moreover, even on CTF3, the control of beam losses will become much more important in the future, in particular for the CLIC Experimental areas (CLEX) [4]. Quantitative beam loss measurements will be necessary to ensure the good operation of the machine. As a first step, simulations of beam losses and the corresponding e^+e^- showers have been performed using Geant3 [5] in order to define the requirements for the BLM system to be built.

In this paper we present the results of a preliminary test performed in November 2003 on the already existing part of the linac. First the layout of the beam line is described, showing the main components of the accelerator. The technical characteristics of the detector chosen for this test are then described. Finally measurements are compared to Geant3 predictions and the perspectives for the final design of the system are presented.

EXPERIMENTAL SETUP ON CTF3

The machine layout is shown in Figure 1. The beam line is composed of three main parts: the injector, the magnetic chicane and a first accelerating module. A $1.6\mu\text{s}$ long high current beam is emitted from a thermionic DC gun. The electrons enter then a 3GHz bunching and accelerating section, which brings their energy up to 20MeV. The heavy beam loading in the accelerating cavities induces strong time transients and generates energy dispersion. The beam head experiences a higher accelerating field than the rest of the beam. The energy gain per accelerating cavity for the leading edge of the beam pulse can be as high as twice the nominal value (7MeV). On top of that any variation of the beam current along the pulse duration will induce a corresponding energy variation. A cleaning chicane consisting of a set of four dipole magnets and a tungsten slit-collimator is used to remove the undesired part of the beam energy spectrum. Dipole magnets create a dispersive region, where the horizontal position of the particles is correlated to their energy. By displacing the slit and varying its width, a well defined part of the beam energy spectrum can be selected. The beam is then sent to the linac modules. Every module is composed of quadrupoles, which ensure the transverse focusing, then two 3GHz accelerating structures and one monitor (BPM) measuring the beam position and current [6]. The beam misalignment is corrected using vertical and horizontal steerers installed in each module just upstream the first cavity. In November 2003, only the first module was installed.

Figure 1. The CTF3 beam layout

The design transverse optic [1] has been calculated so that the beam is focused between the two accelerating cavities. Its size re-expands then as electrons propagate to the next set of quadrupoles. For this reason, there is a high probability for beam losses to be concentrated near the quadrupole regions where the beam is large.

We have installed two beam loss monitors downstream the second set of quadrupoles as shown on Figure 1. As we will show later, the beam transient from the first part of the linac is lost at this location if it is not stopped in the cleaning chicane. The detectors are Aluminum Cathode Electron Multipliers (ACEM) from Hamamatsu [7]. They are only sensitive to charged particles, generating secondary electrons on a thin aluminum layer (100nm). Several amplification stages bring up the current of these secondary electrons up to a level strong enough to be measured directly. The gain of this amplification is controlled by adjusting the bias voltage on the different stages. ACEM's has a fast time response of the order of few nanoseconds which allows the observation of the time evolution of the beam losses with good resolution. This is a very important feature in order to identify the time slice of the beam when losses are concentrated. A gain calibration curve made at CERN using a radioactive ^{137}Cs source is shown in Figure 2.

Figure 2. Calibration curve of an ACEM using a radioactive source

The ^{137}Cs source is a β emitter with energies up to 514keV (94%) and 1.176MeV (6%). Using an intense source with an activity of 330Mq, the output current of the ACEM is directly measured as a function of the high voltage bias. This detector is suitable for the detection of beam current from 100nA to 100mA.

During the test on CTF3, the ACEM's output signals are directly acquired on a 1GHz bandwidth oscilloscope. The gain calibration made using the ^{137}Cs source has been verified with beam losses in the linac. A value equivalent to the slope of the fitted curve of Figure 2 is found for operating voltages from 300V to 500V. The results are summarized in table 1. The values, indicated in mA, correspond to the incident electrons current passing through the detector to measure a signal of 1V amplitude on the oscilloscope.

Table 1 : ACEM calibration			
High Voltage (V)	500	400	300
Incident beam current (mA)	26.5	75.7	177

SUPPRESSING THE BEAM TRANSIENT IN THE CHICANE

A first set of measurements has been performed in order to observe the initial beam transient suppression in the cleaning chicane. This is done by varying the width of the slit and looking at the beam current transmission through the chicane. The beam current signals seen by the BPM502, located just after the chicane, are shown in Figure 3.

Figure 3. Time evolution of the beam current on BPM502 for different slit widths.

When the slit is being closed, the first part of the beam is stopped in the collimator, and in consequence the signal on the BPM502 is shortened. This illustrates the time energy correlation due to transient effects. At the same moment, beam loss

measurements are done as shown in Figure 4. The ACEM signal has a maximum when the slit is completely opened and it is being reduced as the slit is closed. The correlation between the signals from the BPM502 and the ACEM is very good. When the slit is opened, the full beam enters the accelerating section. The steady state part of the beam and the transient are then accelerated further up to 35MeV and 80MeV respectively. Since the transverse optic is matched to 35MeV electrons, the beam transient is not propagated correctly and lost near the quadrupole region where the ACEM sits.

Figure 4. Time evolution of the beam loss measured by the ACEM for different slit width

LOCALIZING THE BEAM LOSS USING BPM'S AND BLM'S

As a second step, the BLM measurements are compared to the expected shower simulations from Geant3. It is shown [5] that in order to obtain quantitative measurements of the beam losses, a large number of detectors must be installed all along the accelerator. To measure the beam loss intensity and position with a good accuracy, detectors should be installed every about 50cm. In our test, only a few monitors had been installed, and the BLM measurements alone cannot be used to determine both the intensity and the position of the beam losses. In order to benchmark Geant3 predictions, the intensity of the beam loss is measured using two consecutive BPM's. The lost beam current is calculated from subtracting the signal of the BPM690 from the signal of the BPM502. Once the beam loss intensity is known, the signal from the ACEM is used to determine the longitudinal position of the losses.

In the actual test, by changing the steering conditions we displace the beam position and thus varying the position of the beam loss along the linac. We compare the beam current lost evaluated using the BPM's in Figure 5a with the beam losses measured by the ACEM in Figure 5b. The two curves correspond to two different steering conditions.

Figure 5. (a) Lost beam current as a function of time. (b) Beam loss current measured by the ACEM as a function of time.

To interpret these measurements, some simulations have been performed in order to evaluate the transverse distribution of the e^+/e^- showers in the realistic environment of the machine assuming. Since the shower depends on the beam energy, two extreme cases have been considered assuming 35MeV and 80MeV electrons. Each simulation assumes a punctual beam loss occurring at different locations: center of the 1st quadrupole, center of the 2nd quadrupole, center of the 3rd quadrupole, and two positions closer to the ACEM where the electrons are lost on the beam pipe. The results are expressed in terms of the shower efficiency, which represents the e^+/e^- shower current measured by the ACEM normalized to the beam loss current. A

summary of the shower efficiencies obtained for the two different beam energies is given in the table 2.

Table 2 : e^+e^- Shower efficiency from Geant3 simulations					
Beam loss position	1 st Quad	2 nd Quad	3 rd Quad	90cm	30cm
Shower efficiency (%) at 35MeV	$5.25 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$	$9.3 \cdot 10^{-3}$	$2.7 \cdot 10^{-2}$	0.2
Shower efficiency (%) at 80MeV	$4.6 \cdot 10^{-3}$	$8.9 \cdot 10^{-3}$	$4.5 \cdot 10^{-2}$	$9.9 \cdot 10^{-2}$	0.28

The shower efficiencies can be calculated by normalizing the curve in Figure 5b with the curve in Figure 5a. The measured efficiencies are reported as a function of the current in a steerer for the transient in Figure 6a and for the steady state part of the beam in Figure 6b.

Figure 6. Shower efficiency measurement under different steering conditions. (a) for the beam transient. (b) for the ‘steady state’ part of the beam.

When the beam is centered, the measured efficiency for the beam transient is compatible with a loss located downstream the 3rd quadrupole. This value decreases as the beam is steered: the position of the loss is displaced upstream the detector in the direction of the 3rd quadrupole. The big error bars present in the case of the beam core

come from the noise of the beam current signal shown in Figure 5a. This illustrates the fact that the beam current losses can not be measured from two consecutive BPM's with accuracy better than the 1% level just for one beam passage.

CONCLUSION

A beam loss monitoring system is under development for the CTF3 linac and a preliminary test was done on the machine. Due to the heavy beam loading in the accelerating structures, beam losses were concentrated at the beam leading edge. During the test the beam current lost in the first part (~50ns) of the pulse can be as high as 100%. However the initial beam transients can be easily suppressed in the momentum cleaning chicane by stopping the highest energy electrons.

Beam loss measurements were in good agreement with the Geant3 simulations. The e^+/e^- showers measured by our 40mm diameter detector were as high as 1mA for 35MeV electrons. This corresponds to shower efficiencies of the order of 10^{-4} . During the test, the beam losses were concentrated at a well defined position of the linac section, near the quadrupoles region, where the beam size is larger.

During the test, some of the principle features of the system to be built have been tested. To distinguish beam losses from the transient or from the beam core, a 10-20ns time response is required. In order to get the transverse (X-Y) position of the loss, each BLM unit is going to be segmented in 4 individual detectors.

To get a complete mapping of the beam loss, and to provide quantitative measurements, the system becomes very complex in the sense that a large amount of detectors must be installed. The risk of damaging a machine component from beam losses is relatively small and corresponds to an extreme situation that can be detected by other means like the wall current monitors or the beam position and current monitors. Our system will be used as a tool for machine operation and the optimization of the beam transient compensation.

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