EXPANSION OF THE FAST LINAC PROTECTION SYSTEM FOR HIGH DUTY CYCLE OPERATION AT THE TESLA TEST FACILITY

H. Schlarb, M. Staack, K. Wittenburg, D. Pugachov, DESY, D-22603 Hamburg, Germany
Y. Cernousko,I. Krouptchenkov, A. Ivanov, S. Makonin, IHEP, 142284 Protvino, Russia
V. Gorbunov, V. Gretchko, Inst. for Nuclear Research of RAS, 117312 Moscow, Russia

Abstract

To perform a proof of principle experiment of a SASE based Free Electron Laser operating a permanent magnet undulator has been installed in the TESLA Test Facility (TTF) linac. The type of permanent magnets (NdFeB) used is known to be sensitive to irradiation. Already losses of the order of 10^{-6} at nominal TTF beam current can cause a degradation of the undulator magnets after a few month of operation. To protect the undulator against radiation a collimation system in front of the undulator removes the electrons with large betatron motion. To detect beam halo or dark current escaping the collimators a beam loss monitor (BLM) system based on photomultiplier has been developed. During the past two years the BLM system has been improved in its electronic components and detectors. It has become a standard tool for linac operation and is now integrated part of the linac protect system. In this paper the design, the operation experiences and the performance limits of the system are presented.

1 INTRODUCTION

The TESLA Test Facility linac is a superconducting linear accelerator whose purpose it is to demonstrate that a linear collider based on superconducting cavities can be built and operated reliably. The linac is constructed from two 12 m long acceleration modules, each is comprised of a string of eight 9-cell cavities operated at 1.3 GHz frequency. A laser driven photoinjector provides the TESLA 500 large bunch spacing ($\approx$ μs) and high bunch charge (few nC). The low emittance beam produced in the rf gun of the injector opened up the possibility to drive a Free-Electron Laser (FEL). For that, three undulator modules with an overall length of 15 m have been installed in summer 1999. Permanent magnets are used to achieve the high magnetic field quality required to initiate the FEL process [1]. Investigations on the radiation threshold of the used NdFeB magnet type predict 1% reduction of the magnet remanent field at an absorbed dose of 70 kGy deposited by charged particles with energies above 20 MeV [2]. Derived by tracking calculations the highest dose can be collected in the magnets if i.e. electrons from the beam halo are lost due to an improper orbit in the vertical plane. In this case the electrons are dumped within a few centimeter at the entrance of vertical focusing quadrupole in the undulator. The calculated absorbed dose at different vertical positions along the undulator is shown in Fig. 1. The peak value reaches 1 kGy for an electron incidence of 1 kJ. With 800 μ macropulse duration, an average current of 8 mA and a rep. rate of 10 Hz and a beam accelerated to 230 MeV the nominal beam power of the TTF linac amounts to 15 kW. If, for example, 1000 hours operation at the nominal beam current I_{nom} is assumed the dose threshold of 70 kGy can be collected at a loss rates of $1.3{\cdot}10^{-6}$. The existing protection system based on toroids stops beam operation at losses in the percent range which is totally insufficient for the protection of the undulator.

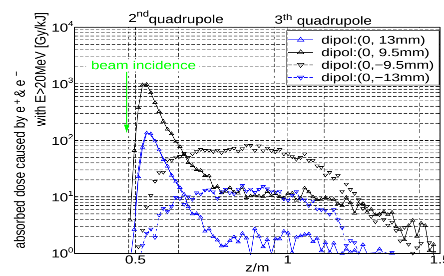

Figure 1: Absorbed dose in magnets for vertical incidence.

To avoid damages of the undulator an upstream collimation system cleans the beam from its halo. Due to energy bandwidth limitations small fractions of the collimated beam might be dumped in the undulator. In this case, an active system is required to reduce the beam current and to monitor the losses when the linac parameters are tuned. In addition, doses can also be collected due to secondary particles produced at the spoilers of the collimation system. The tolerable losses at the spoilers are limited to I_{loss}/I_{nom}=1% [3]. Another limitation is the production of neutrons causing an equivalent dose outside the tunnel shielding [4]. At 230 MeV, the permanent losses should be less than about 0.6% at the collimator section shielded by additional concrete blocks and less than 0.06% at the remaining high-energy sections of the linac.

2 LOSS DETECTORS

Beam losses are detected either by photomultiplier (PM) equipped with scintillator or by secondary emission photomultipliers (SEM) equipped an aluminium cathode. The latter is used in locations with high radiation levels, i.e. at the collimator section. The SEM-type detector [5] is sensitve to high energy gammas and X-rays, beta particles and neutrons, and has been developed for measurements in the MeV and the GeV regions [6]. Small scintillator plates (5cm$\times$3cm$\times$0.5cm) are used along the linac, while

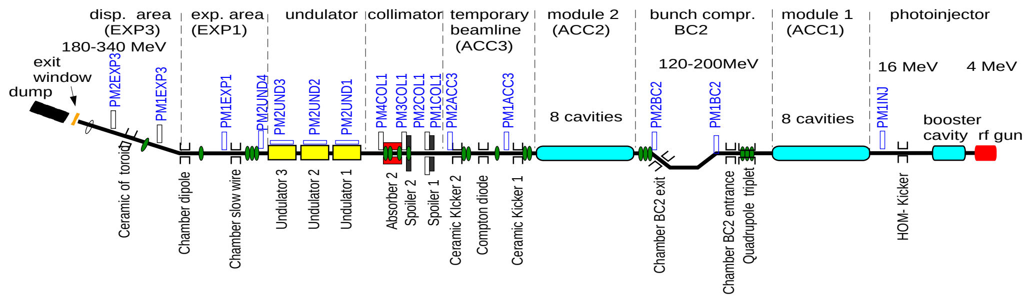

Figure 2: Scheme of the photomultiplier distribution in the TTF linac.

long scintillator rods (400cm$\times$4.3cm$\times$0.5cm) are mounted parallel to the undulator vacuum chamber. High capacitors are added to the voltage divider of the PM to increase the average PM currents delived in the macropulse duration (<1 ms). The capacitors are charged between the beam pulses (>99 ms). The high voltage (HV) power supplies are remote controlled and a read out is possible once per second. Values bewteen -700 V and -1500 V are applied. By a resistive divider placed between the last dynode and zero potential a DC-offset proportional to the HV ($\approx$ 10 mV) is add to the output signal. The DC-offset allows an integral check of the cables, the connections, the active electronic devices and provides an independent monitoring of the HV.

3 EXTENTION TO ENTIRE LINAC

The toroid based protection system has been designed originally for a bunch repetition rate of 216 MHz delivered by a thermionic gun during TTF phase 0. Bandwidth limitations of the toroids together with small differences in their fabrication cause difficulties to operate the toroid based protection system in the entire bunch train, if bunch spacing of 1 MHz or 2.25 MHz are adjusted. To demonstrate the TTF performance at high duty cycle and large beam loading, in December 2000, the BLM system has been extended to the entire linac with a distribution of the PMs shown in Fig. 2. Based on tracking calculations and operational experience, the PMs have been installed at locations where beam losses can be expected. However, if magnets are set to totally wrong currents a failure of the BLM system cannot be excluded. To gurantee proper magnet settings, the toroid based interlock system is active during first 30μs of a macropulse. Because the time constants of linac devices which have an influence on the beam orbit like i.e. superconducting modules or the magnets are much larger than the bunch spacing and thus sudden jumps in orbit cannot be induced. This reduces the number of positions where PM have to be mounted in order to detect any beam losses of a macropulse in the linac.

3.1 Signal processing

The PM signals are split actively to provide independent signals to the control room, to the interlock system, to an offset-level trigger and to a fast integrator. The PM pulses with typically 20 ns FWHH are too fast to be digitized by the ADC which is triggered by a 1 MHz clock from the TTF timing system. A broadband (>300 MHz) fast integrator with reset time of 30 ns for discharging the capacitors and with a variable integration time has been developed. For our purpose 1 MHz reset is chosen corresponding to the acquisition of the ADCs. The rms-signal noise of the fast integrator is less than 5 mV. The signals of PM1COL1 and PM2COL1 before and after integration are shown in Fig. 3. The DC-offset causes a linear slope on the integrated signal and shifts the baseline recorded in the control system. If the HV is adjusted to a proper value the baseline shift is removed by software. The PM signal causes a rapid voltage drop at the middle of the integration period. The ADC signal in a macropulse detected by a PM at the last undulator module is shown in Fig. 4.

3.2 Beam interlock

If the detected signal of the photomultiplier exceeds an adjustable threshold (NIM discriminators), then the macropulse is interrupted within 2.2 μs via the laser pockels cell. The various PM channels are collected in a so called beam interlock concentrator (BIC) which is connected to the laser system. The channels in the BIC causing the interlock event are displayed in the control system. In TTF a short and long pulse operation mode is defined ($\leq 10\mu$s or $\leq 800\mu$s). Long pulses are permitted only if all PM signals are below the interlock thresholds. The PMs in the linac are masked for the BIC during the first 8μs. Since

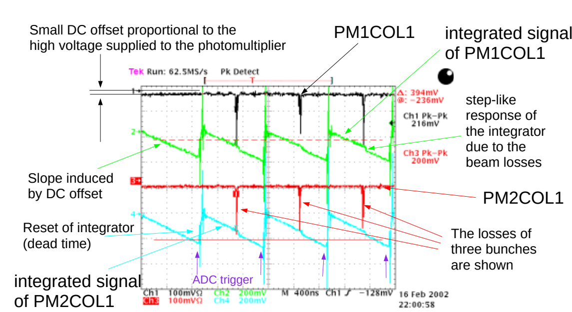

Figure 3: PM signal before and after integration .

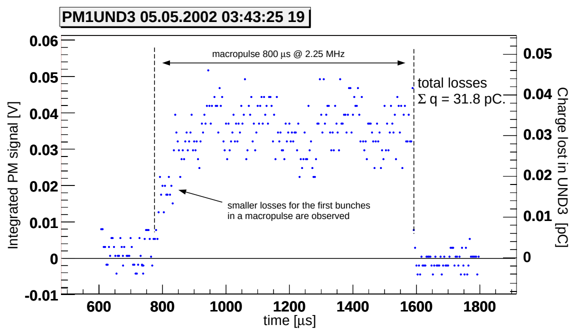

Figure 4: PM signal recorded by the control system.

2.2μs are required to cut the laser pulse train, losses in the linac in the short pulse operation mode have no influence on the number of bunches, but allows to detect whether the long pulse mode is permitted or not. The higher losses due to the mask of the BIC is tolerable, but is required for several experiment where the beam is lost in the linac. The interlock for the undulator section is always active and the beam has to be dumped in the collimator section if a proper transport cannot be achieved.

The offset-level tigger detects the DC-offset voltage on the PM signal. If the DC-offset is too low, hence the HV of the PM is adjusted to an intolerable small value, the machine operation is stopped. With the offset-level trigger 10 V difference in the HV can be resolved.

In the present state of the BLM system the losses due to dark current can be monitored but does not switch off the rf-components where the dark currents are emitted. Due to the 1.3 GHz emission rate of the dark current a simple discriminator cannot be used anymore. The BLM system in TTF phase 2 will be able to distingues between the two type of losses with a higher variability to set the thresholds.

3.3 PM calibration

To determine the relation between the processed PMs signal and the lost charge is the most delicate part of a BLM system. The information is required in order to adjust the interlock threshold neither to tight which restrict the linac operation nor to relaxed which can cause damages of the device to be protected. First, one has to realize that a calibration constant converting measured PM voltages to charge (pC/V) usually depends on the way the losses are induced. For example, a PM mounted behind a tapered collimator would detect a smaller or large value depending on the longitudinal position the electrons incidence the taper. For the most relevant components, the spoilers in the collimator section and the magnets in the undulator, the dependence on the beam incidence have been studied by Monte Carlo calculations. The detector position and its sensitive volume have been chose such that the geometrical impacts on the conversion factors are minimized.

Two different methods have been used for calibration. In case the PM is rather insensitive then the transmission of the beam is measured by toroids while beam losses are induced at the specific device in a controlled way. The method requires that saturation of the loss monitor occurs above the resolution limit of the toroids. In case the PM

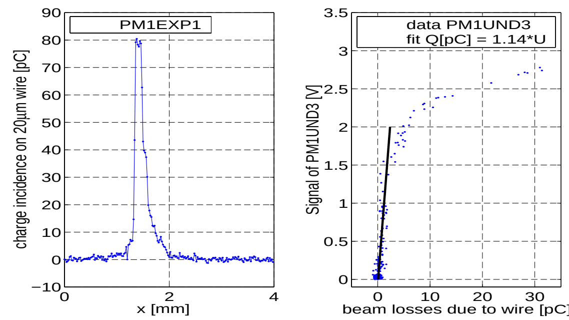

Figure 5: Beam profile (left) and PM calibration (right).

is very sensitive as required for the undulator the losses have been induced by a 20 μm tungston wire of a scanner. By numerical simulations the possible beam losses inside the undulator magnet are compared with the artificially induced losses by the wire which provides the geometrical impact factor for the calibration. The charge hitting the wire is extracted from the beam profile. For PM1UND3 the result is plotted in Fig. 5. Only the beam tails are used for the linear fit because at charges above 5 pC the PM response is non-linear. The interlock threshold has been adjusted to 0.04 pC, or I_{loss}/I_{nom}=$1{\cdot}10^{-5}$ at 2.25 MHz bunch spacing, sufficient for a 1 Hz operation. To meet the requirements at higher linac rep. rates the amplitude of the HV has to be increased from 1500 V to 1700 V. At about 1800 V the radition background in the linac due to dark currents triggers the interlock system and the BLM cannot be operated futher more.

4 CONCLUSION

The beam loss monitor system developed meets the requirements to operate the linac at its design parameters. The resolution limit is given determine by the radiation background due to dark currents.

5 REFERENCES

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