DESIGN CONSIDERATIONS FOR A NEW BEAM DIAGNOSTICS FOR MEDICAL ELECTRON ACCELERATORS

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Abstract

A new beam diagnostics system is under construction at the Siemens AG Healthcare Sector facility in Rudolstadt, Germany. The project goal is to develop, commission and operate a beam diagnostics system to characterize the compact medical linear electron accelerators and help improve the quality of their output beam. A brief system description together with the main electron beam parameters is given. The diagnostics will allow the characterization of the compact linear accelerators by measuring beam intensity/charge using a toroid, transverse beam profile using scintillating screens and transverse beam emittance by means of the quadrupole scan method. In the longitudinal plane the energy and energy spread will be determined using a spectrometer magnet.

INTRODUCTION

Built at the Siemens Healthcare Sector facility in Rudolstadt, Germany, the compact S-Band (2998 MHz) linear electron accelerators are employed in the medicine field of radiotherapy in the energy range 5-21 MeV. Lately, with some redesign work done on them, the compact accelerators are also employed in the field of industrial non-destructive testing (NDT) [1] in the lower region of their energy range. Different performance requirements call for a diagnostics setup to characterize the linear accelerators from an engineering perspective and help meet the overall accelerator design goals. The main operating parameters of the linear electron accelerators to be characterized are listed in Table 1. The whole diagnostics system comprises 3 main components: a high power rf supply unit together with its control console, the beam diagnostics line and a control cabinet connected to the various diagnostics and to a PC for control, data acquisition and processing. The high power rf supply unit encloses a high power modulator used to drive a tunable rf power source. This provides through a pressurized waveguide the required megawatt pulsed rf-power to the linear accelerator in order to accelerate electrons. An automatic frequency control loop compensates for effects like beam loading, or thermal drift thus ensuring that the rf power source and linear accelerator operate at resonance during beam-on time. The linear accelerator structure is of side-coupled type and employs a thermionic triode gun as electron source.

Table 1: Main Specifications of the Siemens S-Band Compact Linear Electron Accelerators [1]

Parameter	6 MeV	21 MeV
Output Electron	6 MeV	5-21 MeV
Output Current	max. 85 mA	max. 120 mA
Operating Frequency	2998 MHz	2998 MHz
RF-pulse length	4.2 μs	4.2 μs
RF-repetition rate	up to 300 Hz	up to 220 Hz

BEAMLINE OVERVIEW

A simplified schematic overview of the beam diagnostics beamline is presented in Fig. 1. The main components of the diagnostics beamline are as follows:

- One non-intercepting transformer for current measurement at the output of the linear accelerator.
- Three transverse beam profile measurement stations, each one accommodating screen holders for YAG:Ce scintillating crystals and optical transition radition (OTR) screens.
- Three stepper-motor driven linear stages for screen holder movements.
- Three optical transmission beamlines, each with a macro-zoom lens and CCD-camera at its end.
- One steering magnet with orbit control provision for both transverse axes.
- Two quadrupole magnets for transverse emittance measurements and also to increase the resolution of the energy measurements.
- One 60 degree spectrometer magnet for energy and energy spread measurements.
- One dry scroll, one turbomolecular and three ion getter pumps to evacuate the beamline.
- One vacuum gauge for UHV monitoring.

BEAM DIAGNOSTICS

The beam diagnostics was designed and awaits to be commissioned for the characterization of linear electron accelerators. Its modular and upgradable design includes provision for the measurement of beam intensity, transverse beam profile using YAG:Ce scintillating screens and OTR, transverse beam emittance and energy as well as energy spread.

Beam Intensity

A non-intercepting and commercially available fast current transformer (FCT) [2] is foreseen for beam charge and current measurements. The FCT is mounted in-air over the beamline right at the output of the linear accelerator to characterize its transmission efficiency (output to injected current ratio) at various operating regimes. The FCT is enclosed by a metal shielding box. A ceramic gap brazed into the beamline is employed to interrupt its electrical conductivity. The FCT will cover the whole beam current range

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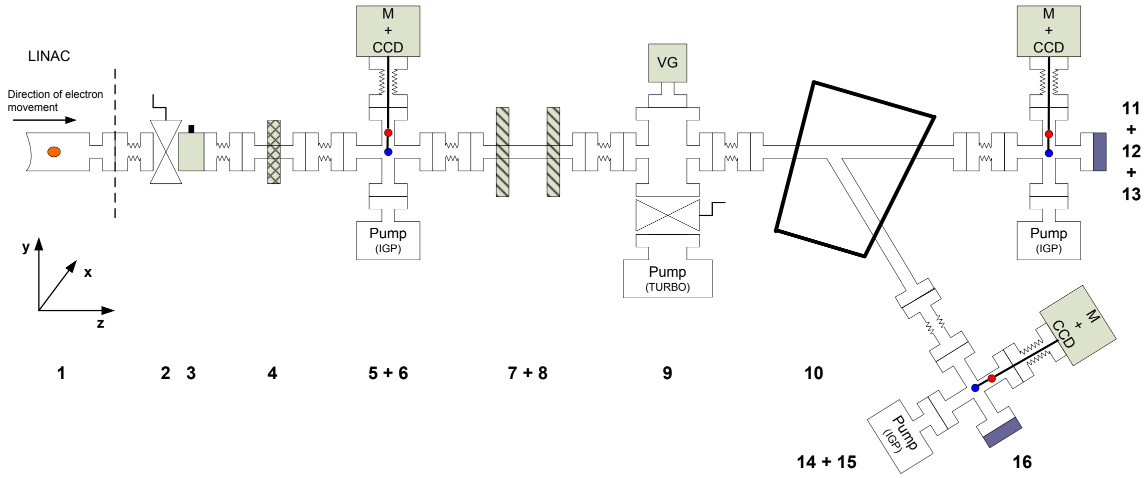

Figure 1: Schematic overview of the modular diagnostics beamline, including (1) the electron gun with the accelerating structure, (2) a gate valve, (3) FCT, (4) steering magnet, (5, 6, 11, 12, 13, 14, 15) transverse beam profile measurement stations with screen holders on linear stages together with ion getter pumps, (7, 8) quadrupole magnets, (9) turbomolecular pump with vacuum gauge and gate valve, (10) spectrometer magnet, (13, 16) beam dumps.

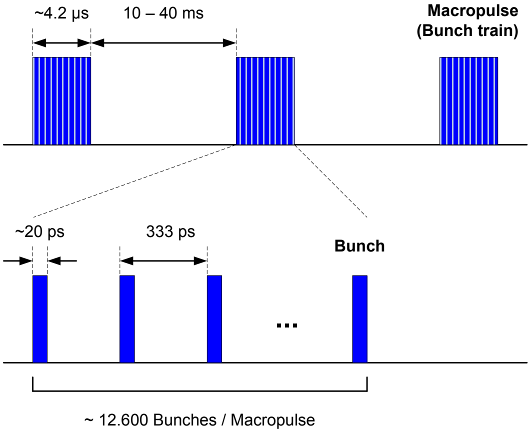

Figure 2: Microbunch and macrobunch time structure of rf pulses of a S-Band linear accelerator structure [3].

listed in Table 1 and will be connected to a fast oscilloscope for direct signal readout. A low-noise coaxial amplifier will be inserted between the FCT and the oscilloscope for low current (< 1 mA) measurements to push the signal above the oscilloscope's noise floor.

The time resolved structure of the electron bunches is depicted in Fig. 2. The whole macrobunch pulse duration is $\sim$4.2 μs and consists of $\sim$20-30 ps [3] long microbunches. The pulse repetition rate of the macrobunches may be up to 300 pps. The fine microbunch structure of the electron beam won't be resolved by the bandwidth limited (2 GHz) FCT, but its fast rise time will allow rendering of the macrobunch waveform. At the current stage intercepting current measurement methods like Faraday cups aren't implemented, but may be added in the future.

Transverse Beam Size / Profile

Three optical diagnostic stations for transverse profile measurements are positioned along the diagnostics beamline. Two in the straight section, one directly at the accelerator output and the second downstream of two quadrupoles and dipole magnets for emittance measurements. The third optical diagnostic station is mounted in the dispersive section after the dipole magnet for energy and energy spread measurements. Each optical diagnostic station consists of a YAG:Ce scintillating crystal [4] and an OTR [5] screen mounted on a stepper-motor driven linear stage, an optical beamline and a 12-bit digital CCD camera. As scintillating materials are sensitive to the time structure of the electron macropulse [6], YAG:Ce was considered to be the best compromise in terms of emission wavelength, photon yield and decay time. Other scintillators like CsI:Ti or GOS:Tb have very long decay times and would saturate under the operating conditions presented in Fig. 2. On the other hand, OTR is an electromagnetic process being insensitive to the time structure of the electron macropulse. AVT Prosilica CCD cameras (1/2") with a resolution of 782x582 pixels and a pixel size of 8.3x8.3 μm are able to acquire images at a maximum frame rate of 64 fps, transmitting the images over Gigabit Ethernet lines. The photons emitted at the screens are collected and imaged via a 0.5 m long optical line to the cameras. A macro-zoom lens is mounted in front of every camera allowing a magnification range from 0.066x to 1.0x. A neutral density filter may also be inserted into the optical beamline, if necessary. The cameras are mounted sideways in a 90 degree angle to the beamline and are surrounded by lead blocks to reduce the radiation dose seen by the electronics and minimize parasitic effects due to scattered x-rays to image processing. The emission wavelength of the YAG:Ce scintillating crystals reaches a peak at 550 nm, being matched to the range where the em-

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ployed CCD cameras are most sensitive.

Image acquisition and processing is implemented in LabVIEW. Background images (only with dark current) will be acquired followed by beam profiles. The background images will be averaged and then substracted from the images with beam profiles. The resulting denoised images will be further filtered using a combination of median filters. Finally, rms parameter extraction and fitting are foreseen.

Transverse Beam Emittance

Analytical calculations and simulations with Particle-In-Cell tracking codes for different injection currents and energy schemes were performed. The laminarity parameter R_0 described by Eq. 1 quantifies the degree of space charge effects versus emittance pressure [7] in the particle distribution and is $\ll 1$ over the whole operating range in Table 1

$$R_0 = \frac{I\sigma_0^2}{2I_0\gamma\epsilon_n^2} < 5.409 \cdot 10^{-3} \ll 1 \qquad (1)$$

where I is the beam current, I_0 is the Alfven current, γ is the relativistic Lorentz factor, σ_0 is the rms beam size and ϵ_n is the normalised transverse emittance. Simulation results of the rms transverse beam size σ_x (x-axis) along the drift space between the quadrupole magnet and the imaging screen downstream was negligible, see Fig. 3. Thus the quadrupole scan method [8] can be employed for transverse emittance measurements.

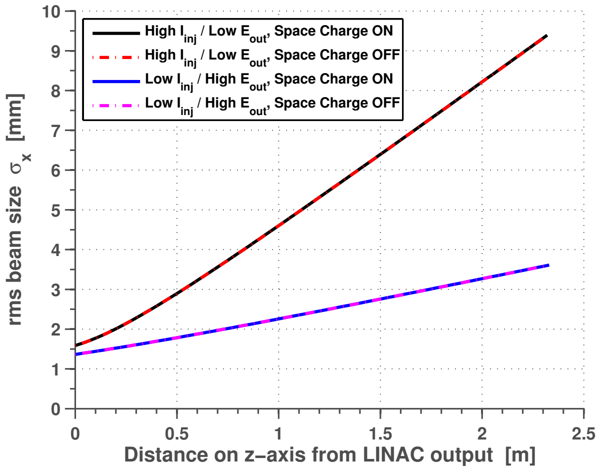

Figure 3: Simulation of rms transvere beam size evolution along a drift space for high injection current at low output energy gain and low injection current at high energy gain in the accelerator.

Energy and Energy Spread

The mean energy and the energy spread of the electron beam are measured with a 60 degree (with respect to the straight trajectory) dipole spectrometer employed to deflect the electrons into a dispersive arm. The electrons are allowed to drift for about ~0.5 m downstream of the dipole in the dispersive section before being imaged at the screen station. The energy distribution is reconstructed from the imaged electron distribution at the screen station as a function of the spectrometer current and position on the screen where the electrons impinge upon. The resolution of the energy spread measurements can be improved by using a focusing quadrupole (in the dispersion plane) placed upstream of the spectrometer magnet.

Experiment Layout

A control PC running LabVIEW handles the communication with the control cabinet, acquires images from the CCD cameras and performs off-line image analysis and machine parameter extraction. The PC contains a network card with four dedicated Gigabit-Ethernet transceivers and communicates with the CCD cameras via GigE-protocol. The CCD cameras are triggered externally with TTL-compatible signals via dedicated lines to ensure real-time synchronization with the control unit. Communication with the control cabinet and monitoring is handled over a 100 Mbit Ethernet line. The control PC allows the operator to conduct fully automated beam size, transverse emittance and energy spread measurements.

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