

RESEARCH AND DIAGNOSIS OF BEAM PARAMETERS IN THE SKIF LINEAR ACCELERATOR

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Abstract

The fourth-generation synchrotron light source Siberian Ring Photon Source (SKIF), located in Novosibirsk, Russia, underwent the tuning of its linear accelerator segment successfully. By deploying a designed beam diagnostic system, crucial parameters of the beam including beam transverse and longitudinal dimensions, energy spread, emittance, and current, were accurately measured. To achieve these measurements, the system was equipped with several fluorescent screens, Cherenkov radiation detectors, a dipole energy spectrometer, and a Faraday cup. This paper elaborates on the design, mode of operation, and practical applications of these diagnostic devices during the accelerator's tuning process. Further, potential areas of optimization for these diagnostic methods are explored to provide feasible directions for enhancing the performance of the linear accelerator. These precise diagnostic tools have been pivotal in the successful tuning of the SKIF linear accelerator. The results thus gathered will form a significant reference point for the development and refinement of similar accelerators in the future.

INTRODUCTION

The Siberian Ring Photon Source (SKIF) project [1] is a unique project in Russia. Its linear accelerator, part of the injection complex, has parameters that have never been achieved at any other installations operating in Russia. A specially designed diagnostic complex was used to obtain these parameters, and it allowed for successful debugging experiments on the linac at a specially designed stand (Figure. 1).

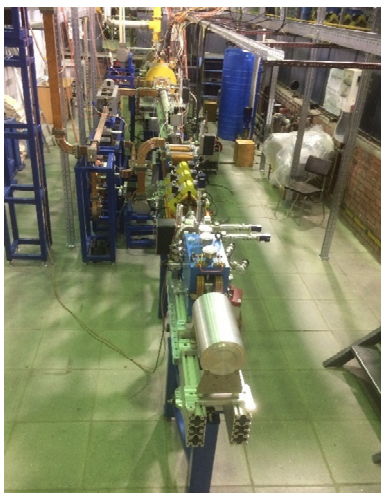


Figure 1: SKIF linear accelerator stand.

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LINEAR ACCELERATOR STAND

A linear accelerator with an electron energy of 200 MeV is used as the injector for the SKIF synchrotron radiation source. The accelerator consists of an RF gun, a third-harmonic grouping device, a pre-accelerator, and a system of regular accelerating structures [2]. The structure of the accelerator used in the experiments is shown in Figure 2.

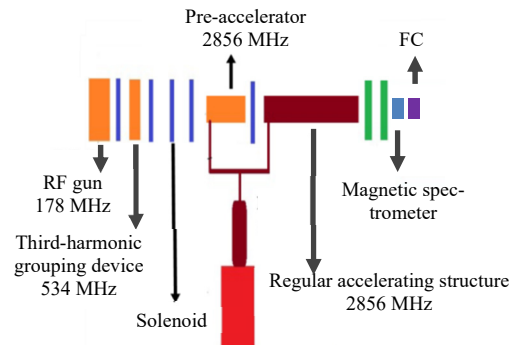


Figure 2: The layout of a linac with a single accelerating structure.

The electron source is based on an RF gun with a 178.5 MHz frequency and a thermionic cathode [3]. This produces an initial beam with an energy of 0.6 MeV. The RF gun operates at 178.5 MHz, which is half of the frequency of the resonator in the booster of SKIF, and one sixteenth of the frequency of the accelerating structure at 2856 MHz. Inside the RF gun, there is an oxide thermionic cathode installed. When the phase of the voltage in the resonator reaches 40 degrees, a trigger pulse is applied for 1 ns to the cathode-grid gap, generating an electron beam. This beam is then accelerated by the field of the resonator to an energy of 600 keV. The gun operates in a pulsed mode, with a repetition rate of 1 Hz. It is also possible to increase the repetition rate up to 20 Hz.

The pre-acceleration system is used to increase the energy of particles to 3 MeV. It includes a drift gap, a pre-accelerator structure, and a 535.5 MHz buncher that reduces the beam duration from 100 ps to 3 ps. This allows for a 1% energy spread at the output of the linear accelerator. A regular accelerating structure is designed to produce beams with energy between 20 and 50 MeV. It is based on a diaphragm waveguide with a constant impedance and an oscillation mode of $2\pi/3$. The structure is powered by a klystron that delivers 50 MW of pulse power. The full version of the linear accelerator has five accelerating structures. The maximum energy gained in the first structure is 53 MeV, and in the next stage it is 42 MeV, with a total maximum beam energy of 221 MeV.

Experiments were conducted at the linac facility using only one accelerating structure, which limited the energy of the electrons to 50 MeV.

Monitoring of beam parameters during different stages of construction, operation, and repair requires the installation of a diagnostic system after each section of the linear accelerator, both during commissioning and normal operation of the linac.

A SET OF LINAC DIAGNOSTICS TO STUDY BEAM CHARACTERISTICS

Phosphor Screens

The transverse dimensions of the SKIF linac beam are approximately $\sigma_{x,y} \approx 2-3$ mm. Therefore, to obtain a spatial resolution of approximately 0.1 mm, it is possible to use screens made of Chromax[®] ceramics or P43 phosphor. Phosphor screens (Figure 3) were placed along the vacuum chamber of the accelerator behind the RF gun, in the grouping channel, behind the pre-accelerator and behind the accelerating acceleration structure to measure the transverse dimensions of the beam, and were also used to adjust the operating mode of the accelerator and the wiring of the beam. The screen has a spatial resolution of 0.03 mm.

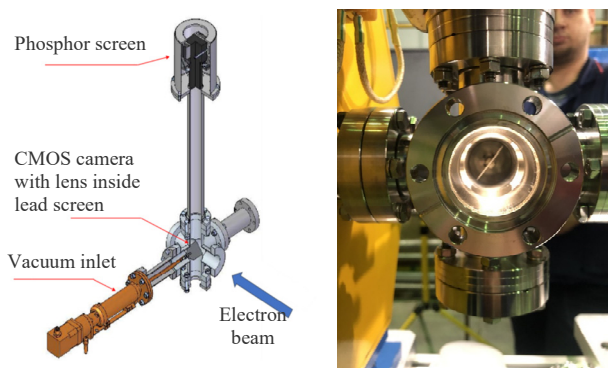


Figure 3: Scheme and photograph of a phosphor screen on the SKIF linear accelerator.

A typical measurement result is shown in Figure 4. The screen has a spatial resolution of 0.03 mm.

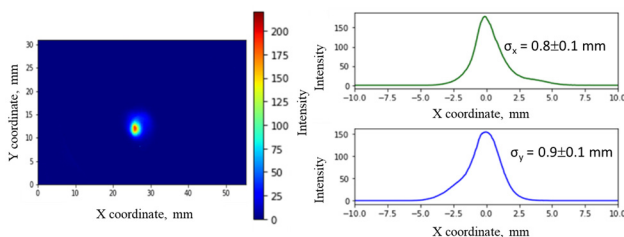


Figure 4: The electron beam profile after the accelerating structure.

The measurements of the emittance of the beam were also conducted using a phosphor screen. The results are presented in Figure 5. The measured value of the emittance is in agreement with the designed one.

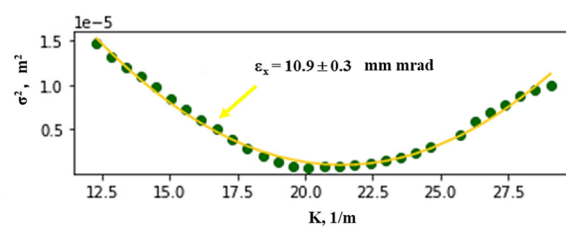


Figure 5: Measurement of the emittance of the beam of the RF gun using a solenoid scan.

Another application of the phosphor screen occurred in connection with the adjustment of linear accelerator debugging plans. The screen was used in conjunction with a dipole corrector to measure beam energy after the radiofrequency (RF) gun, in the bunching channel, and behind the accelerator. Typical measurement results are shown in Figure 6. The accuracy of the energy measurement was within 5%.

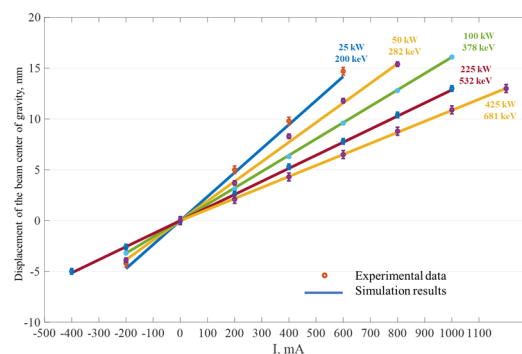


Figure 6: Measurement of the beam energy after the RF gun using a magnetic corrector by its displacement on a phosphor screen.

Magnetic Spectrometer

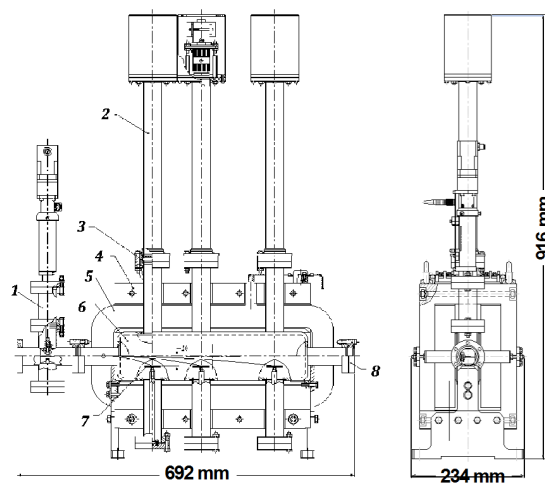


Figure 7: Spectrometer diagram: 1. Beam collimator, controlled by a stepper motor 2. Digital camera unit 3. Vacuum window. 4. Magnetic circuit 5. Magnetic coils 6. Vacuum chamber. 7. Plate with applied phosphor. 8. Titanium foil exit window.

A magnetic spectrometer (Figure 7) has been developed that can measure a wide range of energy levels. This spectrometer is used to determine the energy and energy spread of a beam as different parts of a linear accelerator go into operation.

The beam cross-section at the entrance of the spectrometer is limited by a channel with a width of 0.5 mm passing through a copper collimator that is 3 cm thick (Figure 7). This collimator has an effect on the energy resolution and sensitivity of the spectrometer. The collimator is controlled by a high-precision actuator with a stepper motor, which is of the same model as the one used in the phosphor sensor.

The 3D distribution of the magnetic field strength within the spectrometer was measured as a function of the winding current using Hall sensors. This calibration enabled the spectrometer to be used for measuring the beam energy within the range of 0.5 to 50 MeV.

The accelerator beam, which is limited in cross-section by a collimator at the entrance to the dipole magnet, is deflected by the magnetic field and strikes one of the phosphor screens inside the magnet. The glow from the screen is captured by a digital camera, similar to that used in phosphor sensors. The screens are positioned at distances of 100, 200, and 350 mm from the magnet entrance. The shape and position of the beam impact on the screen allows us to determine the beam's energy and energy distribution.

The image recorded on the third phosphor screen of the magnetic spectrometer is shown in Figure 8. The beam energy used for these measurements was $E_b = 32$ MeV, measured value of the energy spread is $\Delta E = 1.6 \pm 0.1$ MeV (FWHM).

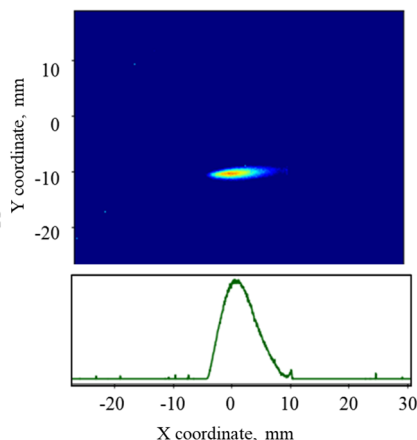


Figure 8: The typical beam image at the 3rd phosphor screen of the magnetic spectrometer.

The accuracy of determining the maximum beam image coordinate is no worse than 0.25 mm, or a resolution of 0.1 MeV for the spectrometer when the third phosphor screen is used. The maximal measured beam energy of linac was 47 MeV that restricted by the power which feed the accelerating structure.

Cherenkov Sensor

The Cherenkov sensor was developed for measuring the duration of the beam based on two types of radiators (see Figure 9). The diagnostic scheme developed allows for time resolution in measuring the beam duration of several picoseconds. The PS-1/S20 streak camera [4] was used to capture Cherenkov radiation.

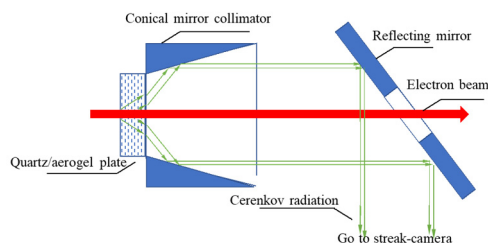


Figure 9: Scheme of the Cherenkov sensor designed for measuring the longitudinal beam profile.

Theoretically, an electron beam with an energy of 0.6 MeV would not generate Cherenkov light in quartz aerogel (with a refractive index of 1.05), so only quartz (with a higher refractive index of 1.46) could be used as a low-energy beam emitter. However, the Cherenkov radiation produced by electrons with energies of 3.5 and 200 MeV in quartz does not leave the flat plate because of total internal reflection. Therefore, aerogel must be used as the radiator. Electrons with an energy of 0.6 MeV undergo strong scattering and absorption in quartz. The optimal thickness was determined through numerical simulations.

The simulation of Cherenkov photon emission was carried out using the FLUKA code. The angular distribution of the Cherenkov radiation produced by a beam with an energy of 0.6 MeV in a quartz plate with different thicknesses is shown in Figure 10.

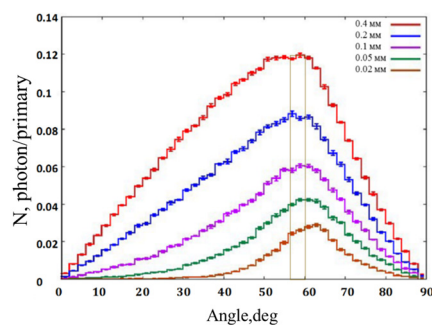


Figure 10: The angular distribution of Cherenkov radiation from an electron beam with an energy of 0.6 MeV passing through a quartz plate of varying thickness is shown. A range of angles between 3.5 degrees is emphasized.

The optimal thickness of the quartz plate is not more than 0.4-0.5 mm. Photons are emitted in a wide solid angle, which is related to the angular and energy distribution of electrons that increase when passing through the quartz plate. Considering the actual solid angle of the optical system, only about 5% of the total photon flux is expected

to reach the photocathode of the streak camera. This corresponds to about 2×10^9 particles, which is sufficient for the applied streak camera to reliably determine the duration of the Cherenkov flash with a time resolution of approximately 3 picoseconds.

The aerogel can be used as a Cherenkov radiator if beams energy exceeds 3 MeV. Based on the data obtained from FLUKA simulations, the total number of photons generated by an aerogel with a thickness of 5 millimeters is approximately 1.5×10^{11} for beam charge of 1 nC. The angular distribution of the photons at the exit of the aerogel is shown in Figure 11.

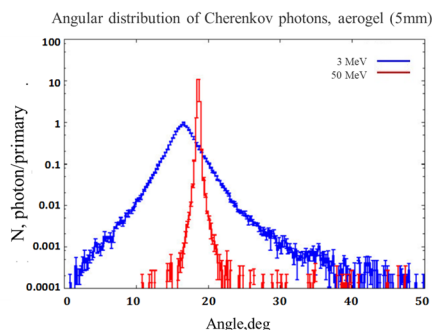


Figure 11: Angular distributions of Cherenkov photons emitted by an electron beam with energies of 3 MeV and 50 MeV as they pass through 5 mm of aerogel.

In total, four Cherenkov detectors were installed in the accelerator complex. They were used to determine the longitudinal particle distribution in the beam, at particle energies ranging from 0.6 MeV to 50 MeV.

The best instrumental function obtained, determined by the size of the light spot from the Cherenkov radiation focused on the photocathode of the streak-camera, was 2.8 ps. This value was achieved at the linac output. A typical longitudinal beam profile recorded using a streak camera is shown in Figure 12.

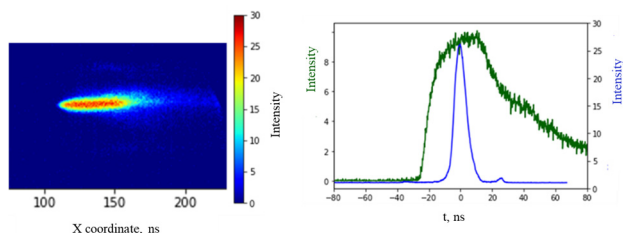


Figure 12: Image at the exit of the streak camera and restored longitudinal beam distribution in the bunching channel, with a beam length FWHM of 60 ps, as recorded by the Cherenkov detector.

Figure 13 combines the simulation results from the ASTRA package (blue curve and dots) with the measurement results (red dots) for the dependence of the FWHM beam length on the RF voltage phase at the RF gun resonator. The two dependencies show good qualitative agreement, suggesting that it is possible to significantly reduce the beam length prior to its passage through the buncher. This is not surprising, as the simulation result

represents the longitudinal dispersion of the beam, which is not necessarily Gaussian in shape.

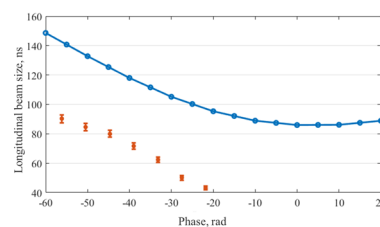


Figure 13: The longitudinal beam dimensions were recorded by the Cherenkov sensor at different phases of the RF gun resonator.

Faraday Cup

Two types of Faraday cups (FCs) are presented in Figure 14. They do not have any special features in their design.

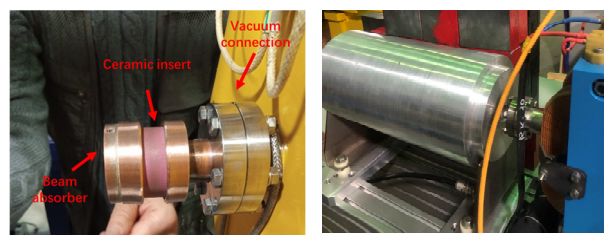


Figure 14: The Faraday cups which were used during the experiments.

One of them (the one on the left) was used to measure the beam charge after the RF gun. The other one (the one on the right) was also used as a beam absorber. The typical signal from the FC and the measured beam charge from the RF gun, depending on the bias voltage applied to the modulator, are shown in Figure 15. The charge was calculated by integrating the signal.

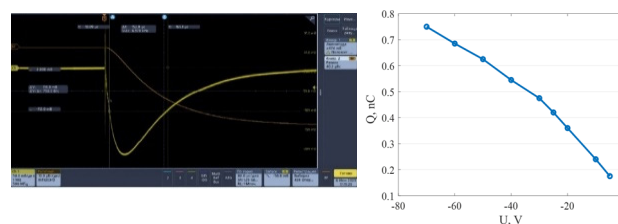


Figure 15: The FC typical signal and the data obtained with it.

CONCLUSION

The paper describes the range of diagnostics used for commissioning and tuning the linear accelerator at SKIF. These diagnostics were successfully applied to measure the electron beam parameters of the linac and contributed to achieving the designed values for the installation.

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