

The UKP-2-1 tandem accelerator complex beam instrumentation and data acquisition systems: operational status and upgrade plan

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Abstract

The UKP-2-1 tandem accelerator complex is located at the Institute of Nuclear Physics, Almaty, Kazakhstan. Its main applications are surface analysis, ion implantation, and irradiation. The complex has two injectors and five beam transport lines. The injectors share a common high-voltage terminal. The first three beamlines are dedicated mainly to proton and light-ion studies, whereas the fourth and fifth are used for heavy-ion irradiation and implantation. The facility operates in two modes. In the first mode, a selected injector and beamline are operated with one ion species produced by either the duoplasmatron or the cesium-sputter ion source. In the second mode, two ion sources and beamlines can be operated simultaneously to irradiate and analyze the same target. Therefore, beam instrumentation, a fully automated control system, as well as a data acquisition system, are essential for the materials-science research program at the UKP-2-1. This paper describes the present accelerator configuration, the operational status of the beam instrumentation, the control system and planned upgrades.

1 Introduction

The UKP-2-1 tandem accelerator complex at the Institute of Nuclear Physics, Almaty, Kazakhstan, was commissioned in 1988 [1, 2]. Originally intended for solid-state physics and low-energy nuclear physics, it has since evolved into a dedicated facility for surface analysis, ion implantation, and irradiation [3, 4]. Since its commissioning, the facility has undergone a series of upgrades to its beam instrumentation, control system, and data acquisition system, and further upgrades are planned. Section 1 describes the accelerator complex and its present configuration. Section 2 presents the control and data acquisition systems. Section 3 describes the upgrade plans.

2 The UKP-2-1 tandem accelerator complex

2.1 General layout and design parameters

The UKP-2-1 tandem accelerator complex is based on two independent acceleration tracts sharing a common high-voltage system. One tract is intended primarily for heavy-ion beams, whereas the second is used for hydrogen and light-ion beams. This configuration allows either independent operation of a single tract or simultaneous acceleration and transport of two ion beams. The complex comprises two ion injectors and five beamlines equipped for different experimental applications. A schematic layout of the accelerator complex is shown in Fig. 1.

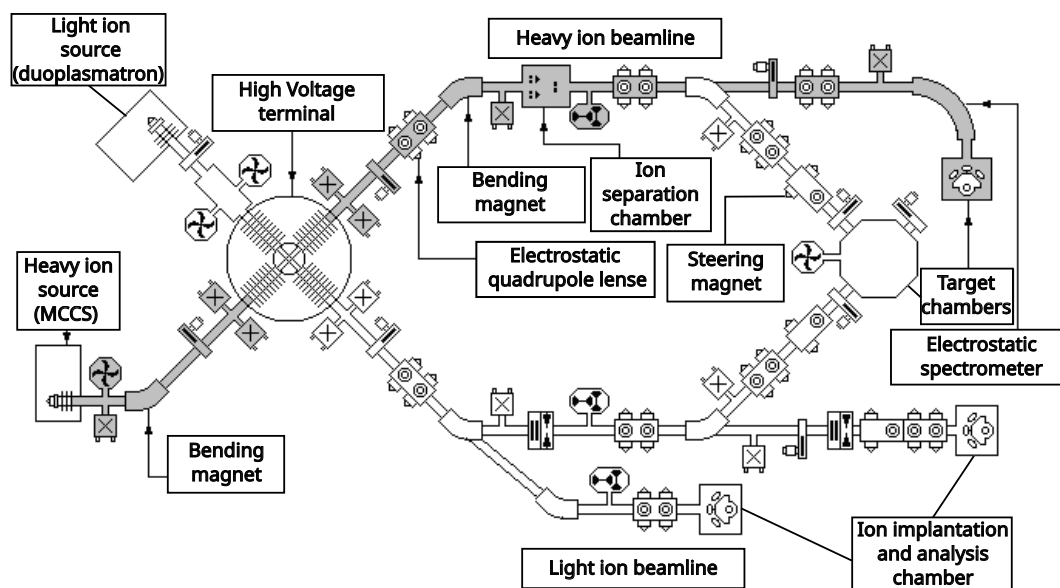


Figure 1: Layout of the UKP-2-1 tandem accelerator complex.

The accelerator system includes low-energy beam transport lines, a common high-voltage terminal, two acceleration tracts, analyzing and bending magnets, electrostatic focusing and steering elements, beam-current diagnostics, and experimental chambers. The main operational parameters of the UKP-2-1 are summarized in Table 1. The maximum terminal voltage is 1 MV. The facility provides ion beams from hydrogen to plutonium with energies ranging from 300 keV to 4 MeV and beam currents at the target ranging from a few nA to tens of μ A. The analyzing magnets

provide a mass resolution of $\Delta M/M = 1/250$, with a magnetic-field homogeneity better than 0.1% and a magnetic-field instability below 5×10^{-5} . The vacuum in the beam transport lines is maintained at 2.3×10^{-7} Torr.

Table 1: Main operational parameters of the UKP-2-1.

Parameter	Value
Terminal voltage	up to 1 MV
Terminal insulation gas	N ₂
Insulation gas pressure	1.5 MPa
Stripping gas	N ₂
Ion species	H to Pu
Beam energy range	300 keV – 4 MeV
Beam current at target	few nA – tens of μ A
Energy spread (proton beam at 1 MeV)	~ 100 eV
Mass resolution of analyzing magnets $\Delta M/M$	1/250
Magnetic field homogeneity	better than 0.1%
Magnetic field instability	$< 5 \times 10^{-5}$
Vacuum in beam transport lines	2.3×10^{-7} Torr

2.2 Injectors and ion sources

UKP-2-1 employs two independent injector systems corresponding to the heavy-ion and light-ion acceleration tracts. The heavy-ion injector is based on a negative-ion source followed by an initial beam-forming system, a 45° mass analyzing magnet, an electrostatic focusing lens, electrostatic steerers, and beam-current diagnostics [1]. The injector provides mass selection and transverse matching of the negative-ion beam prior to injection into the acceleration tract. The heavy-ion injector employs a 40-position multi-cathode source of negative ions by cesium sputtering (MS-SNICS) manufactured by National Electrostatics Corporation [5]. The source allows rapid cathode changes without breaking vacuum, enabling fast switching of the channel to a new ion type. Typical negative-ion beam currents are summarized in Table 2. The heavy-ion beam emittance at the injector output is equal to $2\text{--}4 \pi \text{ mm} \cdot \text{mrad} \cdot (\text{MeV})^{1/2}$.

The light-ion injector was designed for the production and transport of hydrogen and noble-gas ion beams. Its configuration includes a duoplasmatron negative ion source, an initial beam-forming system, electron-separation and neutralization elements, electrostatic focusing, beam steering, and a Faraday cup. The output energy of both injector systems is approximately 50 keV. The beam-current instability over 8 hours of operation does not exceed 10%. The proton beam emittance at 1 MeV and 1 μ A is approximately $2 \text{ mm} \cdot \text{mrad}$. The size of the proton beam on the target is up to 3 mm (FWHM), and the scanning area is up to $20 \text{ mm} \times 20 \text{ mm}$.

Table 2: Ion species currents.

Ion species	Beam current (μA)	Ion species	Beam current (μA)
$^1\text{H}^-$	up to 100	$^{31}\text{P}^-$	100
$^7\text{Li}^-$	3	$^{27}\text{Al}_2^-$	5
$^{11}\text{B}^-$	56	VH^-	10
$^{12}\text{C}^-$	100	$^{59}\text{Ni}^-$	40
$^{13}\text{C}^-$	5	$^{64}\text{Cu}^-$	100
CN^- ($^{15}\text{N}^-$)	20	$^{75}\text{As}^-$	30
$^{28}\text{Si}^-$	500	$^{197}\text{Au}^-$	150

2.3 High-voltage terminal and accelerating system

The accelerating voltage is generated by a symmetric capacitive cascade generator of the Cockcroft-Walton type [6] installed on the common high-voltage terminal. The maximum terminal voltage is 1 MV. The high-voltage and accelerating structures are located inside a pressurized tank that provides electrical insulation. The pressure is equal to 1.5 MPa. The tank is filled with nitrogen.

Four accelerating tubes are arranged in the horizontal plane and form the two acceleration tracts. The corresponding acceleration and charge-exchange regions are vertically displaced, allowing the two ion channels to share the common high-voltage structure while remaining independently transported [1]. The stripping section is located in the terminal center. Nitrogen is also used as the stripping gas.

An energy spread of approximately 100 eV has been achieved in the proton beam at an energy of 1 MeV [2–4]. The energy spread does not exceed 300 eV in various operating modes. The high-voltage stability is 40 V.

2.4 Beam transport lines and end stations

Downstream of the accelerating structure, the light- and heavy-ion tracts employ independent transport systems consisting of electrostatic focusing elements, steering systems, analyzing and bending magnets, slit assemblies, beam-current diagnostics, electrostatic raster scanners, and experimental chambers. The transport line consists of sector bending magnets, with magnetic field monitoring.

The present UKP-2-1 complex comprises five beamlines and five experimental end stations. Three beamlines are associated primarily with proton and light-ion analytical studies, whereas two are used for heavy-ion irradiation and implantation. The analytical program includes Rutherford backscattering spectrometry (RBS), particle-induced X-ray emission (PIXE), and nuclear reaction analysis (NRA) [2–4]. The irradiation and implantation stations employ dedicated target holders and in-vacuum sample manipulators.

2.5 Operational modes

The dual-tract architecture permits two principal operating modes. In the first mode, a single injector, acceleration tract, and experimental beamline are used. Depending on the required experiment, the accelerator can therefore operate with either a proton/light-ion beam or a heavy-ion beam. When both irradiation and subsequent analysis of the same sample are required, the two procedures are performed

sequentially by switching between the corresponding ion sources and beamlines.

In the second mode, both injector systems and acceleration tracts are operated simultaneously. This configuration allows a heavy-ion irradiation or implantation experiment to be combined with proton-beam analysis of the same target. The simultaneous-beam capability is incorporated into the UKP-2-1 design and remains one of the distinctive features of the accelerator complex. The central experimental chamber is dedicated to this purpose (see Fig. 1).

Operation in this mode imposes increased requirements on terminal-voltage stability, magnet reproducibility, beam-current diagnostics, control-system coordination, and data acquisition. Consequently, reliable beam instrumentation and automated accelerator control are essential to the present research program. These systems are described in the following section.

3 Control and data acquisition systems

The UKP-2-1 automated control and data acquisition system is an integral part of the accelerator complex. It was designed to improve the reproducibility of accelerator settings, reduce the time required for beam tuning and operating-mode changes, maintain the required beam parameters during operation, record accelerator-state data, and support accelerator calibration [2].

3.1 System architecture

The control system is a unified entity. All accelerator components are controlled from a single operator workstation, and all subsystems can interact remotely. A two-level architecture is used.

The low-level controller interacts directly with the controlled objects. It issues control signals, acquires data, corrects control signals, converts measured data to real units, and transfers it to the upper level in real time. The controller operates in a fixed 20 ms cycle. During each cycle, 1000 measurements are averaged.

The graphical user interface running at the operator PC provides the interface for tuning, mode selection, configuration storage and visualization. Data between the two levels are exchanged using UDP protocol [7].

3.2 Signals preprocessing

The data acquisition system is based on National Instruments 16-bit ADC and DAC boards, implemented as PCI boards. The ADC boards provide a per-channel sampling rate of 50 kHz. Then, normalizing amplifiers match the standard 0-10 V control range to the voltage requirements of individual accelerator elements. The signal-conditioning electronics also convert the measured signals to the input range of the ADC boards. The front-end electronics are designed for noise immunity and protection against overvoltage and overcurrent. Beam current is measured with Faraday cups. Each cup is connected to an independent current-to-voltage amplifier.

3.3 Magnet control automation

The automated magnet system includes electrostatic lenses and two-coordinate deflectors. The corresponding high-voltage supplies accept external reference signals while retaining local manual control. The magnet power and field-control system are also implemented. Calibrated Hall sensors are installed. Six magnets were automated: the injector magnet, two heavy-tract magnets, and three light-tract magnets. The field ranges are 0.2–1.2 T, 0.4–1.7 T, and 0.2–1.0 T, respectively. The setting accuracy is 0.05 mT. The reproducibility and stability of the heavy-tract magnet fields is 0.05 mT and of the light-tract magnets 0.1 mT.

3.4 Software and operator interface

The high-level main control software is programmed in LabVIEW [8]. It runs on the Windows operating system. The lower-level program continuously acquires ADC, logic, counter, and external-instrument data. Then, it performs conversion and filtering. In the next step, it exchanges commands and measurements with the upper-level software. As a result, the upper-level software sends commands to generate the required DAC and logic outputs. The upper-level interface operates in absolute units and provides dedicated tabs for the injectors, high-voltage terminal, tracts, mass scanning, resonance measurements, stored operating programs, and a mnemonic machine overview. The automation system provides energy calibration based on resonant nuclear reactions. The $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction is used, which has 65 resonances in the proton energy range 0.22–2.0 MeV. Ten repetitions of the calibration procedure for the 991.86 keV resonance showed a reproducibility better than 10 eV.

Automatic and manual modes are supported. In manual mode the operator can tune and save accelerator settings, while in automatic mode stored parameters and calibration coefficients are used to reproduce established operating conditions.

4 Upgrade plans

The next stage of the UKP-2-1 development will focus on the automation of transverse beam-profile diagnostics. This subsystem is currently the least automated part of the facility. The beam profiles are measured manually using quartz beam viewers and photographic recording, which limits the achievable reproducibility of beam transport. Also, it prevents the implementation of beam-based feedback loops.

The planned upgrade will introduce CCD cameras at several diagnostic stations along both the light-ion and heavy-ion beamlines. Each station will consist of a CCD camera with a network interface, a quartz or alumina screen, and a lens system. The camera will be interfaced with the lower-level control computer via GigE Vision, and image acquisition will be integrated into the existing LabVIEW control environment. The expected parameters of the transverse beam-profile diagnostics are summarized in Table 3.

The analysis software will automatically fit the transverse profile to a Gaussian or super-Gaussian distribution and extract the root mean square (RMS) beam size, centroid position, and beam ellipticity. These parameters will be displayed in the operator interface and logged for long-term trend analysis. The software will also

Table 3: Expected parameters of the CCD-camera-based transverse beam-profile diagnostics.

Parameter	Target value
Number of diagnostic stations	4 (2 per beamline)
Spatial resolution	$\leq 100 \mu\text{m}$
Field of view	$\geq 30 \text{ mm} \times 30 \text{ mm}$
Acquisition rate	$\geq 55 \text{ frames/s}$
Dynamic range	$\geq 60 \text{ dB}$
Beam current range	$10 \text{ nA} - 1 \mu\text{A}$

provide a beam-based feedback mode: the measured centroid position will be used to generate correction signals for the electrostatic steerers, and the measured beam size will be used to optimize the quadrupole lens settings.

The feedback algorithms will be implemented as proportional-integral (PI) controllers operating on the low-level controllers. The correction signals will be updated at a rate of 10 Hz, which is sufficient for slow drift compensation and for maintaining beam position stability during long-term irradiation and implantation runs. The feedback loops will be integrated with the existing control framework, so that the operator can enable or disable individual feedback channels without affecting the overall machine configuration.

The upgrade is planned in two stages. Stage 1 is dedicated to the installation of the CCD cameras and profile-fitting software, providing automated profile measurement without feedback. Stage 2 will include the implementation of PI controllers and closed-loop correction for the steering and focusing elements. The expected timeline is 6 months for Stage 1 and 3 months for Stage 2.

Conclusions

The UKP-2-1 offers several distinctive capabilities among low-energy tandem accelerator facilities. Its dual-beam mode, in which heavy-ion irradiation and proton-beam analysis of the same target can be performed simultaneously, is an uncommon feature of electrostatic accelerators [9,10]. The two independent acceleration tracts sharing a common high-voltage system allow the energy of the accelerated heavy-ion beam to be stabilized with respect to an intense proton beam and enable depth and thickness analysis of buried layers during heavy-ion implantation. The facility provides a broad range of ion species, from H to Pu, and beam energies from 300 keV to 4 MeV, with beam currents ranging from a few nA to tens of μA . The LabVIEW-based automation system provides magnet-setting reproducibility of 0.05–0.1 mT, terminal-voltage stability of 40 V, and energy-calibration reproducibility better than 10 eV. These characteristics support a broad range of applications in ion-beam analysis, ion implantation, and materials-science research.

Several limitations remain. The mass resolving power of the analyzing magnets, $\Delta M/M = 1/250$, is moderate compared with that of modern high-resolution systems. The terminal voltage is limited to 1 MV. Transverse beam-profile diagnostics are not yet automated and currently require manual intervention. The energy-calibration procedure, although precise, must be repeated after any change in the cascade-generator parameters and periodically during operation. The beam-current

measurement system covers a broad dynamic range but requires different instruments for different current regimes, including current amplifiers, a femtoammeter, and an ion-counting channel, which complicates simultaneous measurements over multiple current ranges.

The accelerator subsystems are integrated into a unified computer-based control system that provides remote operation, beam-current monitoring, beam-optics control, configuration storage, and reproducible machine tuning. Further upgrades will focus on automated transverse beam-profile diagnostics using CCD-camera-based imaging. These developments are intended to provide the diagnostic capabilities required for long-term monitoring of beam parameters and the future implementation of beam-based feedback for the high-voltage and beam-transport systems.

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Conflicts of Interest

The authors declare no conflicts of interest.

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