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IRRADIATION METHODS AND INFRASTRUCTURE CONCEPTS OF NEW BEAM LINES FOR NICA APPLIED RESEARCH

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Abstract

Nowadays space exploration has faced the issue of radiation risk to microelectronics and biological objects. The new beamlines and irradiation stations of the Nuclotron-based Ion Collider fAcility (NICA) at JINR are currently under construction to study this issue. The beamline parameters, different methods for homogeneous irradiation of targets such as scanning, and beam profile shaping by octupole magnets are discussed. A short description of the building infrastructure, magnet elements, and detectors for these beamlines is also given.

INTRODUCTION

The NICA (Nuclotron-based Ion Collider fAcility) project [1] is a new acceleration and storage complex that is currently under construction at JINR. The project includes both fundamental and applied research.

One of the main tasks of applied research at NICA is to study cosmic-ray radiation damage on the health of astronauts and components of microelectronics during space missions. To achieve this goal, new beam lines and stations to create the radiation conditions similar to those in space are currently under development.

In this note new areas and beamlines for applied research and various methods of targets irradiation that will be implemented in NICA are described and discussed [2-4].

NEW IRRADIATION AREAS

Two new areas are organized within the framework of the NICA applied research program. The list of beams parameters which will be extracted from the NICA accelerators to the channels for applied research in each area is given in [4].

Special area-1 (SOCIT) will be used for investigation of radiation damages on decapsulated microelectronics based on a heavy ion linac (HILAC). Short-range heavy ions with the energy of 3.2 MeV/u will be used.

Area-2, is created for Nuclotron extracted beams at medium energies of 150-800 MeV/u, see Fig. 1. Two new stations for applied research will be used for radiobiological research (SODIB) and tests of microelectronic capsulated chips (SODIT). To transport beams to the new stations in area 2, two beam channels SODIB and SODIT are under construction under the JINR-SIGMAPHI contract. These channels will be integrated into the existing Nuclotron-to-VP-1 extraction beam line.

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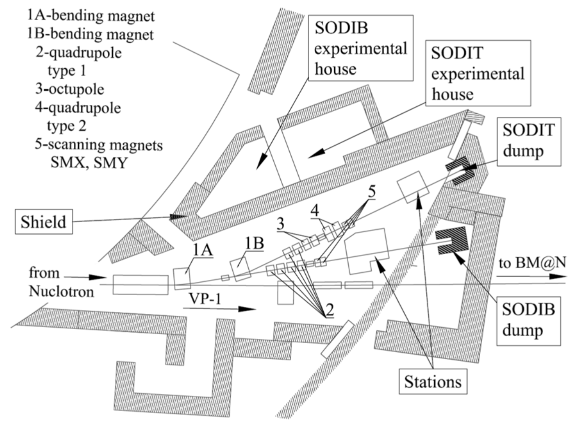

Figure 1: Area 2 infrastructure layout.

IRRADIATION METHODS

The scanning and non-scanning operating modes will be used to provide the large and small beam sizes at the target, respectively. The SODIB and SODIT stations can operate in both modes, while the SOCIT station operates only in the non-scanning mode. The parameters of the magnets and their positions in the channels were defined by beam dynamics simulation using the MAD-X code [4, 5]. One of the main conditions required for irradiation of samples is the beam distribution homogeneity at the target area.

In the SOCIT channel, a 73-mm-wide beam is shaped by quadrupole magnets. The beam envelope in the SOCIT beam line is presented in [3].

Due to a space limitation imposed on the overall length of the SODIT channel, two octupole magnets are also required in the non-scanning mode. The particle distribution on the target was calculated by tracking of 5 × 105 particles in the MAD-X program, see Fig. 2.

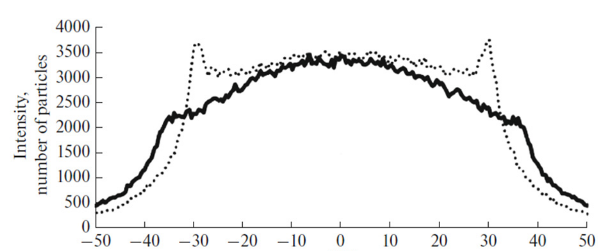

Figure 2: Transverse particle distribution in horizontal (dotted) and vertical (solid) planes on the target as a function of transverse coordinates.

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At the SODIB station, in addition to quadrupole magnets, a collimator with an adjustable inner diameter from 10 mm to 100 mm will serve to provide a sharp boundary of the irradiation field area in both scanning and non-scanning modes.

A spiral and a string scanning mode will be used at the SODIB and SODIT stations. A pair of orthogonal scanning magnets (SMY and SMX) will deflect the beam following the specified excitation current of time function, thus shaping the required particle distribution profile with a large target area.

The beam dynamics calculations for the 3-Hz repetition frequency show that the beam homogeneity at the 100 × 100 mm^2 target is better than 5%. It can be reached for 1.58 s and 1.42 s of the target irradiation time for a spiral and a string mode, respectively.

MAGNET SYSTEM

In addition to the existing dipole magnets that serve to direct the beam from the Nuclotron to the channels [4], the new irradiation channels require a number of different types of electro-magnets. For the SOCIT channel, two existing quadrupole magnets similar to those in the HILAC-Booster transfer line are used [6].

The SODIT and SODIB channels will be equipped with new scanning magnets, two new families of quadrupoles and new octupole magnets.

The design and manufacturing of new magnets with their supports and of power supplies for scanning magnets is undertaken by SIGMAPHI according to JINR's technical specification. Table 1 lists the main requirements.

To reduce the overall costs for the magnet system, the magnet designs already existing at SIGMAPHI were accepted as a starting point. In the JINR-SIGMAPHI collaboration, the designs were optimized to meet the specific requirements for the irradiation channels.

The engineering design, manufacturing drawings, quality assurance and magnetic measurement program have been recently completed and approved. The magnets are presently under manufacturing at SIGMAPHI; the delivery to JINR is planned for spring 2022.

The outcome of the electromagnetic design study is summarized in the next subsections.

Electromagnetic Design

The magnets modelling and optimization was performed by the OPERA 2D and OPERA 3D finite element programs. OPERA 2D was used to design the pole profile and the yoke cross-section. Optimization of the pole end chamfer profile required that the integrated field quality be performed by 3D simulations.

Scanning magnets Two horizontal and two vertical scanning magnets are needed for the irradiation channels. The magnets have a common design, except for the support structure.

Figure 3 shows a mechanical layout of the horizontal magnet. The 140-mm-aperture magnet has an H-type yoke and two bedstead-shaped, water-cooled excitation coils. The yoke consists of two halves, made of 1-mm-thick electrical steel sheets to ensure operation in the scanning mode with the repetition rate of up to 3 Hz. The maximum integrated field strength of 0.29 T·m is provided by 120 turns per coil with the current of 395 A.

Table 1: Main Requirements on the New Magnet for the SODIT and SODIB Channels

	Scanning	Quadrupole		8-pole
Parameter	**SMX/SMY**	**Type 1**	**Type 2**	
# magnets	2+2	6	2	2
Gap/bore Ø (mm)	140	108	160	105
Field/ Gradient (T, T/m, T/m^3)	±0.8	0.6-5.4	0.2-1.4	1098
L_{eff} (mm)	356±4	492±2	480±2	505±3
Good Field region (mm)	H×V 60 x 60	Ø 100	Ø 128	Ø 90
Rel. integrated field error ×10^{-3}	< ±5	< ±5	< ±5	< ±5
Operating mode	Scanning f=0.5-3 Hz	DC	DC	DC

The magnet pole and end chamfer profiles were optimized to reach the required integrated field quality inside the good field region up to Bmax = 0.8 T in the full operating range of the magnet, see Fig. 4.

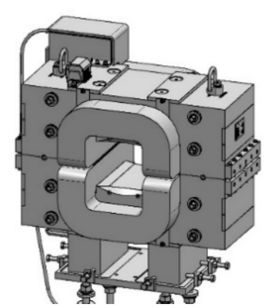

Figure 3: SMX scanning magnet - mechanical layout.

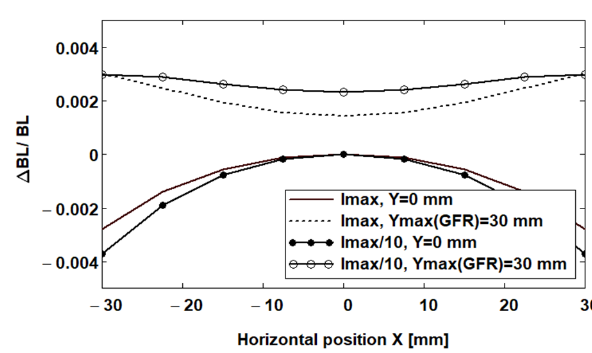

Figure 4: Relative integrated field errors inside the good field region for two values of excitation current.

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Quadrupole magnets The quadrupole magnets of type 1 and type 2 with an aperture diameter of 108 mm and 160 mm, respectively are needed for the channels.

The magnets were modified with respect to the reference SIGMAPHI designs to better conform with the required operating field range in the applied channels, which is few times lower than the one the magnets were initially designed for. In particular, poles and end chamfer profiles were optimized for both types of quadrupole, to provide a better integrated strength homogeneity, see Fig. 5. Also, the number of cooling circuits for type 1 were reduced by a factor of 3. For type 2, the low field level allowed air cooling of the coils by natural convection instead of water cooling as in the original design. That simplified the structure, reduced the manufacturing costs and increased reliability of the magnets.

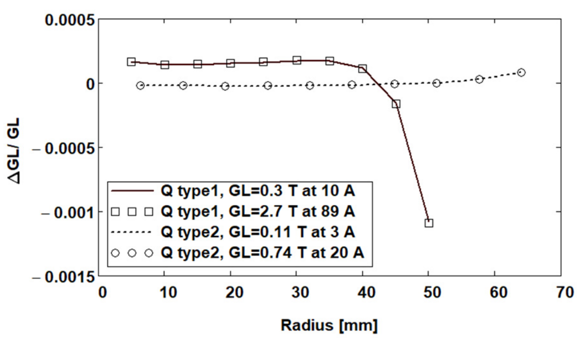

Figure 5: Relative errors of integrated average gradient in the median plane for type 1 and type 2 quadrupoles at min. and max. values of excitation current.

Octupole magnets Two octupole magnets will be installed in the SODIT channel to shape the beam profile in the non-scanning mode. The magnet is assembled from two half-yokes and 8 air-cooled coils, see Fig. 6.

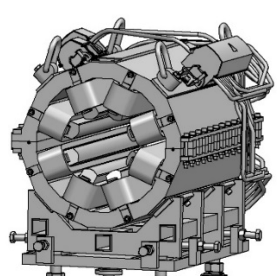

Figure 6: Mechanical layout of the octupole magnet.

The relative multipole coefficients obtained by the Fourier analysis of the radial field component, integrated on a cylinder surface of the good field region are less than 1×10^{-3} and meet the specifications.

DETECTORS

To monitor beam parameters is of high importance for applied research, such as irradiation of biological samples and microelectronics, where precise dose-response data are required. The three types of detectors will be used for beam diagnostics in the irradiation channels: an offline multiwire proportional ionization chamber scintillation fiber detector and an online scintillator detector. The offline systems duplicate each other to get more reliable results.

The diagnostics and corrector system of the HILAC-Booster channel will be used to control the beam in the SOCIT channel [6].

It is important to note that beam diagnostics in each of the beam lines will be in conjunction with the beam diagnostics at the stations. Beam diagnostics will be performed in the "tuning" and "irradiation" modes. The diagnostics involves measurements of the following irradiation parameters: the ion beam profiles, the primary ion fluence, the primary ion density flux, the secondary particle flux density and the radiation dose. The diagnostics systems of the stations are discussed in [7].

As multiwire ionization chamber must be out of vacuum, they are installed in a vacuum-tight chamber which can be moved in and out like a drawer, fitted with windows designed to reduce as much as possible the scattering. Scintillating fiber-based [8, 9] detectors 100×100 mm^2 and 75×75 mm^2, also movable in and out the beam path with minimum scattering, will also be used. Accuracy of Ion flux and beam measurement will be ±10% with 2 mm spatial resolution.

The last sensors are also SciFi based detectors with 20×20 mm^2 sensor distributed in 4 quadrants for beam adjustment, ion flux density and beam profile measurement. Each sensor will be motioned by a stepper motor with an accuracy better than 0.1 mm.

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