NUCLOTRON NEW BEAM CHANNELS FOR APPLIED RESEARCHES

A.Butenko, O.Kozlov, E.Syresin, G.Trubnikov, Joint Institute for Nuclear Research, Dubna, Russia
A. Bakhmutova, A. Bogdanov, A. Golubev, R. Gavrilin, A. Kantsyrev, D. Liakin, N. Markov, V. Panyushkin, V.Skachkov, S. Visotskyj, Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre «Kurchatov Institute», Moscow, Russia

Abstract

Three new experimental areas are organized for applied physics researches in frame of realization of the accelerator facility NICA.

New beamlines are under development for applied researches on Nuclotron accelerator. The ion beams with energy of 250-800 MeV/n extracted from Nuclotron will be used for the radio-biological and materials research and modeling of the cosmic rays interactions with microchips. The equipment of two experimental stations is designed by JINR-ITEP collaboration for these applied researches. The design of the magnetic system, the beam diagnostic equipment, the target stations are developed in frame of this project. The design and construction of these beamlines and experimental stations are planned in 2017-2020.

Low ion energy station will be installed in 2021-2023 inside the transportation channel from heavy ion linac HILAC.

Two new stations for applied researches will be constructed in 2021-2023 with ion beams at energy up 4.5 GeV/u.

NUCLOTRON ACCELERATOR COMPLEX

The Nuclotron accelerator complex at Laboratory for High Energy Physics is the basic facility of JINR for generation of proton, polarized deuterons and protons and also multicharged ion beams in energy range up to 6 GeV/n. This accelerator based on the unique technology of superconducting magnetic system [1]. The Nuclotron accelerator complex includes Alvarez-type linac LU-20, superconducting synchrotron Nuclotron equipped with an internal target station and slow extraction on system and facilities for fixed target experiments located in experimental building of about 10000 m^2.

Different types of the ion beams are delivered for the experiments (Table 1). Increase of the beam intensity and widening of the ion species are related with construction of three new ion sources: SPI (Source of Polarized Ions), LIS (Laser Ion Source), Krion-6T (ESIS type heavy ion source).

Development of slow extraction system resulted in realization of acceptable quality of the extracted beam in the interval of the spill duration from 60 ms up to 20 s and for the beam intensity from 10^{11} down to 10^5 ions per cycle (Fig.1).

Table 1: Nuclotron and Beam Parameters

Parameter	Project	Status
Magnetic field, T	2	2
B-field ramp, T/s	1	0.8
Particles	p–U, d↑	p, d-Xe
Maximal energy, GeV/u	12 (p), 5.9(d)	5.9 (d, ^{12}C)
		3.5 $^{40}Ar^{16+}$
		2.5 $^{56}Fe^{26+}$
	4.5 $^{197}Au^{79+}$	1.5 $^{124}Xe^{42+}$
Intensity, ions/cycle	10^{11} (p,d)	d $2\text{-}5{\cdot}10^{10}$
		$^{7}Li^{3+}$ $3{\cdot}10^9$
		^{12}C $2{\cdot}10^9$
		$^{56}Fe^{26+}$$2{\cdot}10^6$
		$^{40}Ar^{18+}$ $5{\cdot}10^6$
	10^9(A> 100)	$^{124}Xe^{24+}$ $1{\cdot}10^4$

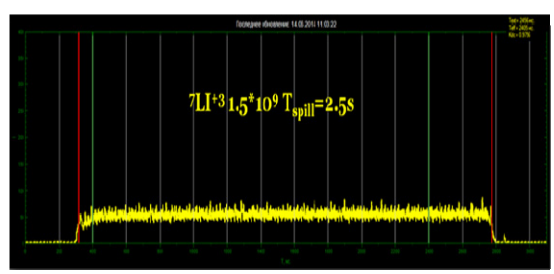

Figure 1: Example of the slow extraction beam spill.

NICA ACCELERATOR COMPLEX

In the nearest future the Nuclotron technology of superconducting magnetic system will be used for new accelerators of the NICA collider facility under creation at JINR [2]. NICA is aimed at generation of intense heavy ion and polarized nuclear beams for searching the baryonic matter of a high density at high temperature and investigation of polarization phenomena.

ISBN 978-3-95450-182-3

The Nuclotron [3] will be main synchrotron of the NICA facility being constructed at JINR. NICA facility will consists of two linacs, booster and Nuclotron, collider rings equipped with two detectors and a few beam transport lines. The Booster is small superconducting synchrotron constructing in the frames of the NICA project to improve the Nuclotron performance. The parameters of light at heavy ions are given in the Table 2 at application of new ion sources and booster synchrotron.

Table 2. The Parameters of Ion Beams at Application of New Ion Sources and Booster Synchrotron

Parameter	Energy, GeV/u	New ion source	Booster
Light ions	6	$5{\cdot}10^{10}$ (LIS)	
Heavy ions		Krion 6T	
$^{40}Ar^{18+}$	4.9	$1{\cdot}10^{8}$	$2{\cdot}10^{10}$
$^{56}Fe^{26+}$	5.4	$1{\cdot}10^{8}$	$1{\cdot}10^{10}$
$^{124}Xe^{48/42+}$	4.0	$1{\cdot}10^{7}$	$2{\cdot}10^{9}$
$^{197}Au^{79+}$	4.5	$1{\cdot}10^{7}$	$2{\cdot}10^{9}$

APPLIED RESEARCHES AT NICA

Three new areas are organized for applied researches in frame of realization of the accelerator complex NICA (Table 3).

Table 3: Three Areas of NICA Accelerator Complex for Applied Researches

Area–1. Low energy beams, Injector HILAC, 3.2 MeV/u	Area–2. Medium energy beams, Nuclotron 250-800 MeV/u	Area–3. High energy beams, Nuclotron < 4.5 GeV/u
Nanotechnology	Radiation damages in microelectronic. Radiobiology.	New materials. Radiation damages in microelectronic. Radiobiology for space. Relativistic nuclear energetics. Utilization of radioactive waste.

The area-2 is created in 2017-2020 for Nuclotron extracted beams at medium energy of 250-800 MeV/u. The Nuclotron transportation channel is modernized. Two stations are under development now for radiobiological researches and testing of microelectronic at radiation damage by heavy ions. The special station will be installed in 2021-2023 inside the transportation channel from heavy ion linac (HILAC) injector to booster. The heavy ions with energy of 3.2 MeV/u will be used for nanotechnologies. Two stations will be constructed in 2021-2023 for applied researches with high energy beams at energy up 4.5 GeV/u. The radiobiology for space, the researches of new materials, the study of radiation damages in microelectronic will be realized in one station. The other station will be used for relativistic nuclear energetic and utilization of radioactive waste.

NUCLOTRON NEW BEAM CHANNELS FOR APPLIED RESEARCHES

The area-2 is under development for applied researches on extracted Nuclotron beams of medium energy of 250 - 800 MeV/u. The optical functions of initial part of existing Nuclotron extraction channel are given in Fig.2 for Z/A=0.5 and ion energy 800 MeV/u. This channel consists of the septum, the Lambertson magnet, the vertical deflection dipole magnet, two doublets of quadrupole lenses, the deflection dipole magnet which used to provide beam transportation in horizontal plane.

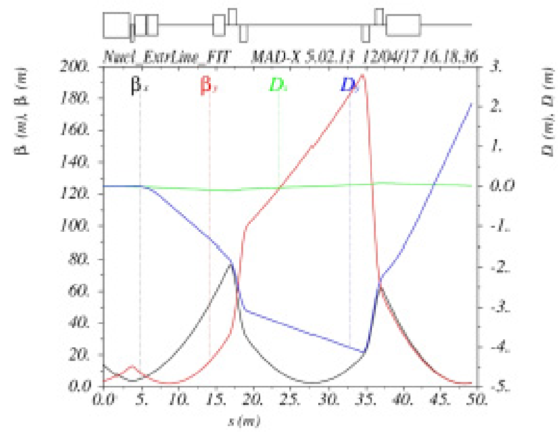

Figure 2: Optical functions of existing initial part of channel for applied researches.

Two new transportation channels are designed with two target stations, one for study of radiation damages in microelectronics and other for radiobiology.

The parameters of ion beams and equipment applied for testing of microelectronic are given in the Table 4. The heavy ion beams extracted from Nuclotron permit to obtain the linear energy transfer (LET) in range of 0.1-100 MeV×cm^2/mg in Si target. The LET threshold for microchip failures corresponds to 60 MeV·cm^2/mg. The microchips are placed inside Si corpus at device package thickness of 10 mm. The heavy ion beams like $^{131}Xe^{54+}$-$^{197}Au^{79+}$ with energy 250-300 MeV/n extracted from Nuclotron are decelerated in microchip corpus to energy of 5-20 MeV/n. The LET in microchip can reach the level of 50-100 MeV×cm^2/mg for heavy ions of these energies.

The sketch of Nuclotron beam channels for applied researches is shown in Fig. 3. Two deflection dipole magnets are used for beam transportation to both stations. The maximal magnetic rigidity corresponds to 13.4 T×m. The maximal magnetic field is equal to 1.5 T, the length

ISBN 978-3-95450-182-3

of the magnets is about 1.8 m. The deflection angle is equal to 11.5^0 at Z/A=0.5.A.

Table 4: Parameters of Ion Beams and Station for Microelectronic Testing of Radiation Damages

Parameter value	Value
Kind of ions	p-$^{197}Au^{79+}$
Extracted ion energy, MeV/u	250-800
Beam emittance, π·mm·mrad	40-10
Beam spill pulse duration, s	2-30
The beam diameter on target, mm	10
Pass in Si, mm	>10
LET in Si, MeV×cm^2/mg	0.1-100
Step in LET, MeV×cm^2/mg	5
Ion flux, p/(cm^2×s)	10-10^6
Irradiation area, mm	200×200
Nonuniformity of flux	±15%
Nonuniformity of flux at area 30×30 mm	±5%
Target temperature diapason at irradiation, ^{0}C	+25 - +125
Irradiation at rotation in two orthogonal axes	-90^0 up $+90^0$
Angle rotation step, degree	1
Target pressure, Torr	10^{-3}, 760

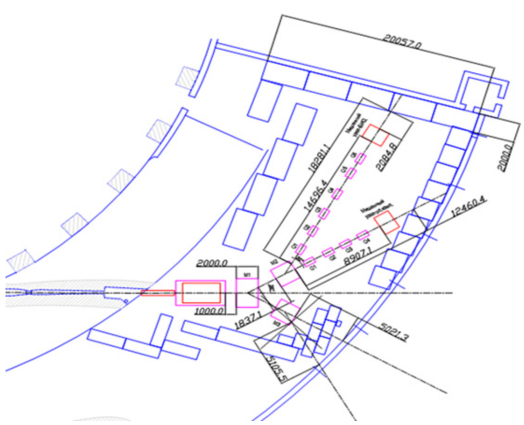

Figure 3: Layout of Nuclotron new beam channels for applied researches.

The scanning vertical and horizontal magnets are used for formation of uniform dose distribution on a large target area of 200×200 mm. The maximal magnetic field in scanning magnets corresponds to 1T, the length of magnet is equal to 0.9 m. The scanning magnets are placed on distance of 3.3 m from target. The extraction of Nuclotron beam is produced at a plateau of magnetic field for fixed ion energy at beam spill duration time of 30s. The scanning time corresponds to 1.5 s along one line in horizontal direction. The ramping rate of magnetic field in scanning magnet is equal to 0.66 T/s. The total irradiation time of target area 200×200 mm corresponds to 30 s. The nonuniformity of ion flux should be less than ±15% on large target area.

The target should be installed on the goniometers, which provide rotation in two orthogonal planes from -90^0 to $+90^0$ with rotation angle step of 1^0. The target irradiation should be done at pressure of 10^{-3} Torr and atmosphere. The target temperature is varied from $+25^0$ up 125^0.

The diagnostic system provides measurements of following parameters: the horizontal and vertical profile of ion beam, the ion fluence, the density of ion fluence, the inhomogeneity of the ion fluence on irradiation area, the radiation dose. The ion fluence is controlled by using the polycarbonate or polyethylene terephthalate track detectors placed in close vicinity of any testing device in all irradiation runs. The scintillators based detectors and ionization chambers are used to determine the beam spatial distribution and flux value. Double side Si strip detector fully covers the beam spot at step of 1 mm.

The accelerator-based researches in radiobiology are essential for improving radiotherapy and ensure protection in space. The heavy ions extracted from Nuclotron are a tool for modeling of biological action of space radiation. Heavy charged particles from Galaxy are the most dangerous type of cosmic radiation. Consequences of action of Galactic heavy ions are related to induction of cancer and formation of gene and structural mutations; violation of visual functions: lesions of retina, cataract induction.

The equipment of radiobiological station permits to irradiate by ions the biological samples and animals like rats and monkeys. The uniform dose distribution will be form in the target with size of 100×100 mm and depth of 100 mm. The diagnostic system is applied for measurements of the ion beam intensity, the horizontal and vertical profile, control of the beam position relatively to target optical axes, the dose space distribution and control of the obtained dose.

REFERENCES

[1] A.M.Baldin *et al.*, "Cryogenic System of the Nuclotron - a New Superconducting Synchrotron", Advances in Cryogenic Engineering, v.39, p.501, New York, 1994.

[2] G. Trubnikov *et al.*, "Heavy ion collider facility NICA at JINR (Dubna): status and development", Proc. ICHEP'12, Melbourne, Australia.

[3] A. Sidorin *et al.*, "Status of Nuclotron", Proc. RUPAC16, p.150, St-Petersburg, 2016.