ACCELERATOR APPLICATIONS FOR BASIC AND APPLIED RESEARCH AT JINR

I. N. Meshkov#, A. N. Sisakian and G. V. Trubnikov, JINR, Russia

Abstract

The description of the accelerators − basic facilities at JINR and the research programs both for basic and applied research being performed at these accelerators is presented in the report. Future development of the basic facilities is discussed as well.

INTRODUCTION: JINR AND ITS ACCELERATOR FACILITIES

JINR is the International Intergovernmental Organization that joins today 18 Member States and 6 Associated Members States. It has about 700 research partners in 60 countries including all leading Laboratories in the World having and using particle accelerators in experimental studies. Traditionally JINR activities are based on "three pillars":

- basic research in high energy and nuclear physics, condensed matter physics and radiobiology;
- education programme;
- applied research based on achievements in basic research.

The list of accelerator facilities operated at JINR includes synchrocyclotron "Phasotron", superconducting proton synchrotron "Nuclotron", heavy ion cyclotrons U400, U400M, U200 and IC100, and electron linac based pulsed neutron source IREN.

PHASOTRON AND MEDICAL APPLICATIONS

Synchrocyclotron "Phasotron" is the first accelerator in Dubna. Constructed in frames of Soviet Atomic Project by initiative of Igor Kurchatov and under leadership of Mikhail Meshcheryakov and Venedict Dzhelepov it was commissioned in 1949 and remains still in operation. Machine accelerates protons up to 660 MeV at the beam current of 2 μA. Research program includes muon-catalysis, pion and muon physics, nuclear physics. However, the main activity at Phasotron is cancer therapy.

The treatment facility contains *7 treatment cabins*: 3 cabins for protons of 100, 130, 200 MeV + proton tomography, by one cabin for protons of 660 MeV, π-mesons of 30−80 MeV, protons or neutrons of 350 MeV and one cabin with γ-source Co-60. The particles used for patient treatment are generated with primary proton beam on targets.

The facility makes treatment for about 100 patients per year.

CYCLOTRONS AT FLEROV LABORATORY OF NUCLEAR REACTIONS

4 isochronous cyclotrons of the laboratory are used for both basic and applied research that is presented here for each of machines, one by one.

Cyclotron U-400 is the main tool *for synthesis of transfermium elements*. It accelerates a wide range of ions from $^{6}Li^{1+}$ up to the heaviest one $^{136}Xe^{14+}$ to the energy of 4÷20 MeV/amu at the extracted current of (2÷60)·10^{12} pps. The experiments on synthesis of transfermium elements have been started and carried out under leadership of Georgy Flerov, the founder of the Laboratory named later after him. His disciple and successor Yuri Oganesian developed this scientific direction: since 1963 up to now there were synthesized 10 such elements [1]. Most efficient projectile used for hot synthesis of elements of the number 113÷118 are ions $^{48}Ca^{5+}$ (5.3 MeV/u, 7·10^{12} pps) and $^{48}Ca^{9+}$ (19 MeV/u, 3·10^{12} pps).

Cyclotron U-400M is used for generation and studies of "exotic" neutron reach nuclei. It delivers accelerated ions from $^{7}Li^{2+}$ (30 MeV/u, 6·10^{13} pps) up to $^{48}Ca^{10+}$ (20 MeV/u, 5·10^{11} pps). At ACCULINA fragment separator with cryogenic ^{2}H and ^{3}H target and ^{12}C target have been performed generation of radioactive ion beams (RIBs) of ^{6}He and ^{8}He and generation and studies of exotic beams nuclei ^{5}H and ^{7}H, ^{10}He, ^{12}He and ^{13}Li [2].

At the beginning of 1st decade of this centure the project *"Dubna Radioactive Ion BeamS" (DRIBs)* has been started at FLNR. It has a goal to combine the U400 and U400M cyclotrons into the accelerator complex for generation of beams of exotic light neutron-deficient and neutron-rich nuclei in reactions with light ions. By the 2008 the 1st stage of the project DRIBS-I has been completed and with primary beam of ^{7}Li (1.9·10^{13} pps) the beam of ^{6}He (5·10^{7} pps) was generated and accelerated in U400M. The 3d stage of the project – *DRIBS-III* is under development presently. This stage includes modernization of U400M and U400 cyclotrons, construction of the new experimental hall (~ 2600м^2), next generation set-ups and high current heavy ion cyclotron DC200 (A≤ 100, E ≤ 10 MeV/u, I ≥ 10 pμA).

Cyclotron IC-100 is used traditionally for applied research and new technologies development. The cyclotron accelerates heavy ions from $^{22}Ne^{4+}$ (1.1·10^{12} pps) up to $^{184}W^{31+}$ (0.7·10^{10} pps) to the energy of 1.0÷1.2 MeV/u. The main technology that have been and being developed with the beams of IC-100 [3, 4] is production of

meshkov@jinr.ru

- different kind and characteristics track membranes with cylindrical pores of the diameter of 5μ–0.05μ at the pore density of 10^6–$3\cdot10^9$ per cm^2;
- track membranes of the new types corresponding to the requirements of the Life Science applied to the production of new medicines and bio-substance;
- metal nano-structures (e.g. nano-wires and submicron pipes);
- ion-implantation synthesis of nano-size cluster structures in the solids.

These technologies find application in medicine, biology, industry… A promising example of track membranes application in technology is design and construction of heat exchange tubes with microstructure layers covering cooling surface: microchannels connecting cooled wall with the cooling liquid stream are operated near boiling temperature. That allows to use boiling heat for enhancement of cooling efficiency – so called vapotron effect.

Next advance in technology development relates to the project of DC-110 cyclotron construction (to be completed by 2012). The cyclotron will deliver heavy ions $^{40}Ar^{7+}$, $^{86}Kr^{15+}$ (both $6.25\cdot10^{12}$ pps) and $^{132}Xe^{23+}$ ($3.12\cdot10^{12}$ pps) at the energy of 2.5 MeV/u.

IREN – INTENSE RESONANCE NEUTRON SOURCE

The IREN source under development at JINR is to be used as a new generation neutron source for research into the wide range of nuclear physics problems both of fundamental and applied character, those as

- search for Time Reversal Invariance Violation effects in neutron–nucleus interactions;
- neutron-induced fission studies;
- fundamental properties of the neutron: mean square charge radius and electric polarizability;
- nuclear structure studies;
- nuclear data collection.

The full-scale scientific research complex IREN will comprise a 200-MeV linear accelerator LUE-200 with a beam power about 10 kW, a subcritical multiplying target, and beam infrastructure with experimental rooms, as well as technological, control, safety and service systems. The characteristics of the full-scale complex IREN (integral neutron yield 10^{15} n/s and pulse width 0.6 μs) will allow it to rank among the best neutron sources of such class GELINA (Belgium) and ORELA (USA). The realization of the project is conducted in several stages. *The first stage* includes the construction of the LUE-200 linear accelerator and nonmultiplying target. This will make possible, already at the first stage, to carry out experiments which require precision neutron spectroscopy in the neutron energy range from fractions of eV to hundreds of eV. The first stage of IREN facility at the Frank Laboratory of Neutron Physics of JINR was commissioned by the beginning of 2009.

Linear electron accelerator LUE-200 consists of the pulsed electron gun, acceleration system (designed and fabricated by the Budker INP), RF power supply system based on 10-cm range klystrons with modulators, beam focusing and transport system including wide aperture magnetic spectrometer and vacuum system. Accelerator is allocated vertically inside 3-floors building. At the 1st stage of the IREN project the nonmultiplying neutron producing target is used. Electron gun has 2 electrodes, one of them incorporates oxide thermocathode of 12 mm diameter. The gun fed by 200 kV pulsed transformer provides pulsed electron beam with 8 A peak current of 250–300 ns duration at 50 Hz repetition rate and emittance of $\leq 0.1\cdot\pi\cdot$mm·mrad.

Acceleration system consists of the RF buncher and 2 short (3 meters long each one) acceleration sections with high acceleration rate. Acceleration sections have structure of traveling wave with constant impedance and high acceleration rate. They are fed by RF power from klystrons – RF power amplifiers of 10-cm frequency range (2856 MHz). During the tests of the acceleration system prototype at foreinjector of the VEPP-5 complex at BINP the maximal electric field of 45 MV/m has been achieved. The average acceleration rate was 35 MeV/m. Full scale accelerator project foresees two sections.

The design version of *RF power supply* assumed application of two SLAC 5045 klystrons which can provide peak RF power of 60 MW at average level of 45 kW. RF power compression system (SLED) is used to provide 3–4 times gain in RF power transfer to the accelerating section providing average accelerating rate up to 35 MeV/m. Due to absence of SLAC 5045 klystrons one accelerating section only was put into operation with TH2129 (Thomson) klystron that provides 20 MW peak power. The second section is replaced with transfer channel containing two quadrupole lens doublets.

Beam focusing and transport system consist of 3 short solenoidal magnetic lenses between the electron gun and the RF buncher where the beam enters long solenoid with magnetic field of 2.4 kG. The first acceleration section is immersed into this solenoid as well. From its exit to the target the beam is transported with the system of magnets consisting of one separate quadrupole lens, four doublets of the wide-aperture quadrupole lenses and six steering coils distributed along the transfer channel.

Neutron producing target is made of tungsten based alloy. It has the form of cylinder of 40 mm in diameter and 100 mm height placed into aluminum can of 160 mm diameter and 200 mm height. Distilled water is circulated inside the can providing cooling of the tungsten target and neutron moderation. Water layer thickness in radial direction is of 50 mm. Both target dimensions and water moderator thickness were optimized with Monte Carlo simulation. Accelerated electrons are penetrating inside the can through beryllium window of 1 mm thick and hit the top surface of the target cylinder. In the target neutrons are generated in two stage process: the electrons stop in the target producing Bremsstrahlung gamma quanta interact with tungsten nuclei and produced neutrons in reactions $^{A}W(\gamma, n)^{A-1}W$, $^{A}W(\gamma, 2n)^{A-2}W$, $^{A}W(\gamma, 3n)^{A-3}W$.

As a result of the optimization of the operational modes of the acceleration and focusing systems the following peak values of the beam current have been achieved [5]: at the electron gun exit – 5.8 A, after acceleration section – 3.5 A, on the target – of 3.0 A (Table 1).

Table 1: IREN Source Parameters – design and stage I

Parameter	Design	Stage I (2010)
Electron energy, MeV	200	30
Peak current, A	1.5	3.0
Beam pulse duration, ns	200	100
Repetition frequency, Hz	150	25÷50
Average beam power, kW	9.0	0.225÷0.450
Target	Pt (multiplication)	W
Average neutron flux, s^{-1}	$1.2 \cdot 10^{15}$	$1 \cdot 10^{11}$

Integral neutron yield was defined with measurement of the neutron flux density at 10 meters distance from the target by means of the ^{3}He gaseous proportional counter SNM-16 and also with the set of activation detectors positioned on the side surface of the target can. The result is presented in Table 1.

The upgrade of the facility with more powerful klystrons and modulators to reach the designed parameters is planned for the period 2010–2015.

NUCLOTRON-M & NICA PROJECT

The **N**uclotron-based **I**on **C**ollider f**A**cility (NICA) is a new accelerator complex (Fig.1) being constructed at JINR. It is aimed to provide collider experiments with

- heavy ions $^{197}Au^{79+}$ at $\sqrt{s_{NN}}$ = 4÷11 GeV (1÷4.5 GeV/u ion kinetic energy) at average luminosity of $1 \cdot 10^{27}$ cm$^{-2} \cdot$s^{-1} (at $\sqrt{s_{NN}}$ = 9 GeV);
- light-heavy ions (colliding beams of the same energy range and luminosity;
- polarized beams of protons $\sqrt{s_{NN}}$ = 12÷25 GeV (5÷12.6 GeV kinetic energy) and deuterons $\sqrt{s_{NN}}$ = = 4÷13.8 GeV (2÷5.9 GeV/u ion kinetic energy).

The proposed facility consists of the following elements (Fig.1):

– *"Old" injector* (pos. 1): set of light ion sources including source of polarized protons and deuterons and Alvarez-type linac LU-20.

– *"New" injector* [6] (pos. 2, under construction): ESIS-type ion source that provides $^{197}Au^{32+}$ ions at intensity of $2 \cdot 10^{9}$ ions per pulse of about 7 μs duration at repetition rate up to 50 Hz and linear accelerator consisting of RFQ and RFQ Drift Tube Linac (RFQ DTL) sections. The linac accelerates the ions at A/q ≤ 8 up to the energy of 6 MeV/u at efficiency not less than 80 %.

– *Booster-synchrotron* [7] housed inside Synchrophasotron yoke (pos. 3). The Booster (pos. 4) has superconducting (SC) magnetic system that provides maximum magnetic rigidity of 25 T·m at the ring circumference of 215 m. It is equipped with electron cooling system that allows to provide cooling of the ion beam in the energy range from injection energy up to 100 MeV/u. The maximum energy of $^{197}Au^{32+}$ ions accelerated in the Booster is of 600 MeV/u. Stripping foil placed in the transfer line from the Booster to the Nuclotron allows to provide the stripping efficiency at the maximum Booster energy not less than 80 %.

– *Nuclotron* [8] – SC proton synchrotron (pos. 5) has maximum magnetic rigidity of 45 T·m and the circumference of 251.52 m provides the acceleration of completely stripped $^{197}Au^{79+}$ ions up to the experiment energy in energy range of 1÷4.5 GeV/u and protons up to maximum energy of 12.6 GeV.

– *Transfer line* (pos. 6) transports the particles from Nuclotron to Collider rings.

– *Two SC collider rings* [9, 10] (pos. 8) of racetrack shape have maximum magnetic rigidity of 45 T·m and the circumference of about 400 m. The maximum field of SC dipole magnets is 2 T. For luminosity preservation an electron and stochastic cooling systems will be constructed.

– *Two detectors* – MultiPurpose Detector (*MPD*, pos. 9) and Spin Physics Detector(*SPD*, pos. 10) are located in opposite straight sections of the racetrack rings.

– *Two transfer lines* transport particle beams extracted from Booster (pos. 11) and Nuclotron (pos. 12) to the New research area, where fixed target experiments both basic and applied character will be placed.

The NICA parameters (Table 2) allow to reach the goals of the project formulated above.

One of NICA accelerators – Nuclotron is used presently for fixed target experiments on extracted beams (Fig. 1, pos. 7). The program of the experiments includes experimental studies on relativistic nuclear physics, spin physics in few body nuclear systems (with polarized deuterons) and physics of flavours. At the same time, the Nuclotron beams are used for research in radiobiology (se next section) and applied research. Most important among the last ones is the experiment "Energy + Transmutation" having the goal of study of the problem related to "energy generation" with subcrtical Pu blankets and transmutation of radioactive nuclides.

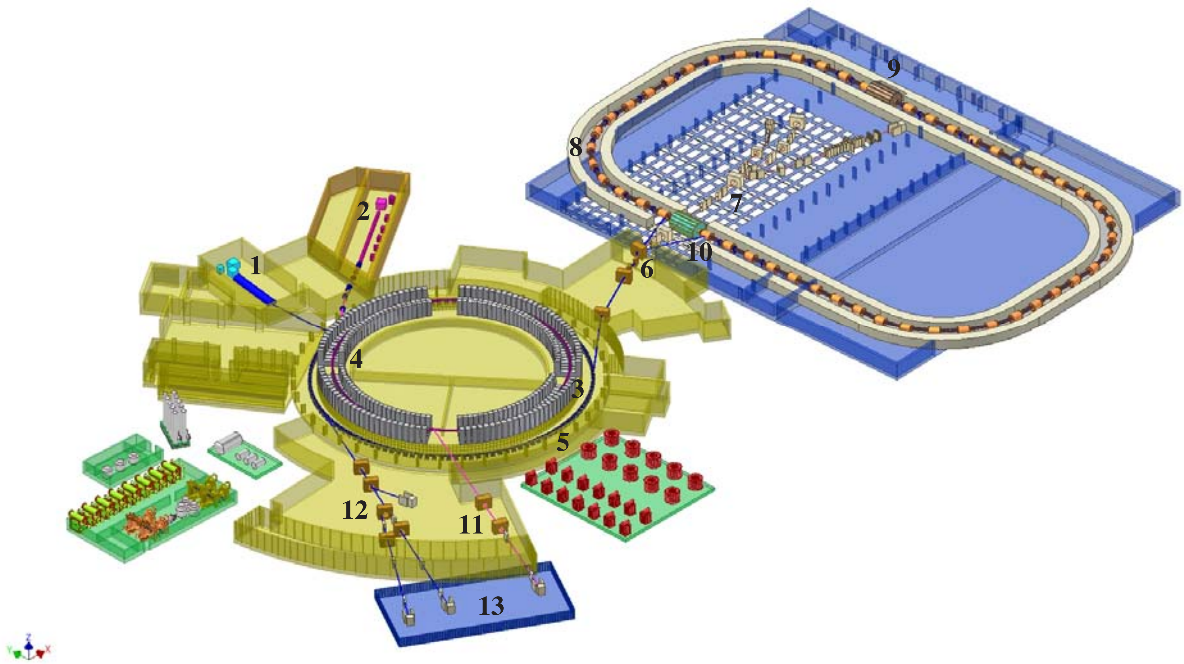

Figure 1: Scheme of NICA facility: 1 – light and polarized ion sources and "old" Alvarez-type linac; 2 – ESIS source and new RFQ linac; 3 – Synchrophasotron yoke; 4 – Booster; 5 – Nuclotron; 6 – beam transfer line; 7 – Nuclotron beam lines and fixed target experiments (to be dismantled); 8 – Collider; 9 – MPD; 10 – SPD; 11, 12 – transfer channels; 13 – new research area

Table 2: Parameters of NICA accelerators

Acceleration	**Booster project**	**Nuclotron**		**Collider**
		Project	**Status (March 2010)**	
1. Circumference, m	212.2	251.5		400
2. Max. magn. field, T	2.0	2.05	1.8	2.0
3. Magn. rigidity, T·m	25.0	45	39.5	45
4. Cycle duration, s	4.0	4.0	5.0	≥ 5000
5. B-field ramp, T/s	1.0	1.0	1.0	0.1
6.Accelerated (stored) particles	p÷ $^{197}Au^{79+}$, p↑, d↑		p-Xe, d↑	p÷ $^{197}Au^{79+}$, p↑, d↑
Maximum energy, GeV/u				
protons	–	12.6	–	12.6
deuterons	$1\cdot10^{10}$	5.87	5.1	5.87
$^{197}Au^{79}$	$1\cdot10^{9}$	4.5	1.0(238Xe^{24+})	4.5
Intensity, ion number per cycle (bunch)				
protons	$1\cdot10^{11}$	$1\cdot10^{11}$	$1\cdot10^{11}$	$1\cdot10^{11}$
deuterons	$1\cdot10^{10}$	$1\cdot10^{10}$	$1\cdot10^{10}$	$1\cdot10^{10}$
$^{197}Au^{79}$	$1\cdot10^{9}$	$1\cdot10^{9}$	$1\cdot10^{6}(Xe^{24+})$	$1\cdot10^{9}$

The heavy ion mode of the NICA project is scheduled for 5 years realization, the facility commissioning is expected in 2015.

RADIOBIOLOGY RESEARCH AT JINR

Application of fast heavy ions to radiobiological experimental studies presents a new quality owing to specific ionization effect on a tissue pattern that is crossed by an ion. Indeed, such a fast heavy ion causes a great damage to DNA molecule provoking so called "stable chromosomal aberrations. Due to this reason heavy ions become a powerful tool for studies of fundamental problems of radiation genetics.

JINR accelerators (Table 3) are actively used for experiments which are performed by The Laboratory for Radiobiology of JINR [11]. One of results of basic character obtained in these experiments clearly demonstrates significantly stronger action of heavy ions on living tissue as compared with gamma rays (Fig. 2) and light particles.

Table 3: JINR Accelerators used in radiobiology research

Accelerator	Particles	Max. energy
Phasotron	Protons	660 MeV
Cyclotron U200	Heavy ions	10 MeV/amu
Cyclotron U400M	Heavy ions	50 MeV/amu
Nuclotron	Ions (d ÷ Xe)	6÷3 GeV

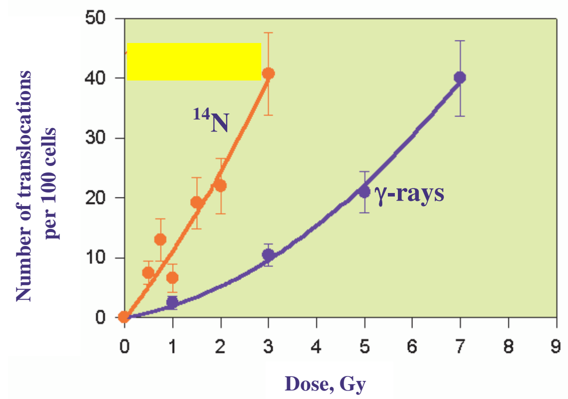

Figure 2: Results of living tissue irradiation with γ-rays (lower curve) and N

REFERENCES

[1] Pure & Appl. Chem., v. 65 (1993) 1757; v. 75 (2003) 1613; v. 76 (2004) 2101; v. 81 (2009) 1331.

[2] G.M. Ter-Akopian et al., Eur. Phys. J. 150 (2007) 61–66.

[3] P.Apel, I.Blonskaya, S.Dmitriev, O.Orelovitch, A.Presz, B. Sartowska, Nanotechnology, 2007, 18, 305302.

[4] G.Bujnarowski, V.Skuratov, K. Havancsak, and Yu.Kovalev, Rad. Effects & Defects in Solids, v. 164, 2009, 409–416.

[5] V.Kobets, I.Meshkov, V.Shvetsov, A,Sumbaev et al., Journal of Phys.: Conf. Series, http://iopscience.iop.org/1742-6596/205/1/012053

[6] V.Kobets, A.Sidorin et al., These Proceedings, MOPD009.

[7] A Butenko, V. Mikhaylov et al., These Proceedings, MOPD007.

[8] A Butenko, G. Trubnikov et al., These Proceedings, MOPD008.

[9] S.Kostromin, O. Kozlov et al., These Proceedings, MOPD010.

[10] I.Meshkov, A.Sidorin et al., These Proceedings, MOPD011.

[11] E.Krasavin, R.Govorun et al, Physics of Part. and Nucl., v. 35 (2004) 797–813.