FLNR JINR ACCELERATOR COMPLEX FOR APPLIED PHYSICS RESEARCHES: STATE-OF-THE-ART AND FUTURE

S. Mitrofanov†, P. Apel, V. Bashevoy, V. Bekhterev, S. Bogomolov, O. Borisov, J. Franko, B. Gikal,
G. Gulbekyan, I. Ivanenko, I. Kalagin, N. Kazarinov, V. Mironov, V. Semin, V. Skuratov,
A. Tikhomirov, Joint Institute for Nuclear Research, 141980 Dubna, Russia

Abstract

The main activities of FLNR, following its name -- are related to fundamental science, but, in parallel, plenty of efforts are paid for practical applications. Certain amount of beam time every year is spent for applied science experiments on FLNR accelerator complex. The main directions are: the production of the heterogeneous micro - and nano-structured materials; testing of electronic components (avionics and space electronics) for radiation hardness; ion-implantation nanotechnology and radiation materials science. Status of all these activities, its modern trends and needs will be reported. Basing on FLNR long term experience in these fields and aiming to improve the instrumentation for users, FLNR accelerator department announce the design study for a new cyclotron, DC140, which will be dedicated machine for applied researches in FLNR. Following the user's requirements, DC140 should accelerate the heavy ions with mass-to-charge ratio A/Z of the range from 5 to 8 up to fixed energies 2 and 4.8 MeV per unit mass. The first outlook of DC140 parameters, its features, layout of its casemate and general overview of the new FLNR facility for applied science is presented.

INTRODUCTION

The main point is that for applied science people use powerful machines which were created and developed to solve the wide range of fundamental research. The usage of 'science' accelerators for such activities is connected which high cost of beam time and difficulty to meet quick changes of user's requirements. Also, there is a "time lack" problem when application begins to demand the beam time more than accelerator centre could provide to it in parallel with its scientific plan's realization. Usually, it means that all technical "bugs" and methodological questions were successfully fixed and answered, and users requesting the time as much as they could. That's why Flerov Laboratory of Nuclear Reaction of Joint Institute for Nuclear Research starts the Design Study of the dedicated applied science facility based on the new DC130 cyclotron. The irradiation facility will be used mainly for the following applications: creation and development of track membranes (nuclear filters) and the heavy ion induced modification of materials; activation analysis, applied radiochemistry and production of high purity isotopes; ion-implantation nanotechnology and radiation materials science; testing of electronic components (avionics and space electronics) for radiation hardness.

RADIATION MATERIAL SCIENCE

Characterization and monitoring of structural defects enhanced by ~100 MeV heavy ions in nuclear ceramics represents an important issue. Besides many intriguing fundamental science questions, these experiments may be of considerable practical value in view of such pressing problems such as radiation stability of inert matrix fuel hosts and coated fuel particles. Materials to be employed as inert matrices for transmuting of minor actinides by means of nuclear reactions should obviously present suitable characteristics as hosts for the actinides and as targets for the irradiation in a reactor. A key parameter to be considered is the resistance to radiation damage due to neutron exposure, gamma and beta radiation, self-irradiation from alpha decay, and fission fragments. Structural modifications induced by fission products, i.e. atoms with a mass ranging from 80 to 155 and an energy of about 100 MeV, still remain uncertain because the effects cannot be investigated using classical low-energy ion implanters. To date, only limited data concerning the microstructural response of non-fertile ceramics to ion irradiation of fission energy are available and external bombardment with energetic ions offers a unique opportunity to simulate fission fragment-induced damage.

The main objective of ongoing projects in radiation material science in FLNR is to determine the radiation tolerance of several oxides, carbide and nitride based ceramics (MgO, Al_2O_3, ZrN, SiC, Si_3N_4, A_lN), considered as candidates for inert matrix fuel hosts, irradiated with high-energy heavy ions, simulating fission fragments impact. Our central objectives are:

a) To study the structural changes and mechanical stresses induced by swift heavy ions as function of ion fluence, irradiation temperature and ionizing energy loss;
b) To elucidate the dense ionization effect on pre-existing defect structures in irradiated materials;
c) To compare the radiation stability of nanocrystalline and bulk ceramics.

TRACK – ETCHING MEMBRANE

In the 1970s, advances in heavy-ion accelerator technology resulted in the idea to replace the fission fragment irradiation with bombardment by high energy, multiply charged ions. The advantages of the accelerator irradiation method are the following: (i) there is no radioactive contamination of the irradiated material because the ion energy is normally below the Coulomb barrier; (ii) all of the bombarding particles are identical; (iii) the ions have a

---

† mitrofanov@jinr.ru

larger penetration depth in the polymers; (iv) it is easier to produce high density track arrays; (v) particles heavier than fission fragments can be used for highly radiation-resistant materials; and (vi) it is easier to control the impact angle to produce either arrays of parallel tracks or those with special angle distributions. The only disadvantages of ion beams are that they are less stable over time because of transient fluctuations in intensity, and they have a higher cost. Firstly, the U-300 cyclotron at the Flerov Laboratory of Nuclear Reactions (JINR, Dubna) was employed to produce a track membrane from a polyester film. Accelerated xenon ions, with energy of 1 MeV/u and intensity of 10^{12} s^{-1}, were found to be a good substitute for fission fragments. High intensity, heavy-ion beams provided new advantages, such as higher pore densities, larger membrane thickness, and control over the angle of incidence. The use of heavy-ion accelerators equipped with specialized beam channels, sophisticated irradiation chambers, and beam diagnostics made it possible to fabricate micro- and nanoporous materials with unique structural parameters that could not be obtained using fission fragments. Since then, following the advances was achieved using FLNR accelerating complex the applications of track membranes can be categorized into three groups: process filtration, analytical filtration, and permeable supports. Within each group, there are a number of particular uses. Typical areas where the use of track membranes are especially beneficial, are air monitoring; water analysis; blood filtration; cell culture; analytical methods (gravimetry, microscopy, emission spectroscopy, X-ray fluorescence, and others); bacteria removal and analysis; HPLC (high performance liquid chromatography) sample preparation; nucleic acid studies; oceanographic studies; healthcare; biosensors. With the capability to create either a single track or regular pattern with a preset number of tracks, the track etching technique allows the fabrication of nano and microengineered membranes, with finely tuned geometrical parameters.

SEE TESTING

On-board equipment of spacecraft is exposed to ionizing radiation from the Earth's natural radiation field, as well as galactic and solar cosmic rays during its operation. There are two types of effects in microelectronic circuits caused by radiation: 1 - those related to accumulated dose; and 2 - those caused by a singular hit of a swift heavy ion (single event effect, SEE). Despite its relatively minor contribution (~1%) of the total amount of charged particles, it is heavy ions that cause the most damage to microelectronics hard ware components due to the high level of specific ionization loss. Hence, to reproduce the effects of the heavy ion component of cosmic radiation for the prediction of electronic device radiation hardness usage of low intensity (up 10^6 ions cm^{-2} s^{-1}) heavy ion beams with linear energy transfer (LET - the measure of energy losses per path length in the material) levels in silicon, specific for the ion energy range of 50 - 200 MeV/u, is supposed. Taking into account that actual integrated circuits in metal and plastic packages, as well as ready to use electronic boards need to be tested, ion beams with energies in the range of 3-50 MeV/u are used in model experiments.

The SEE testing facility was established at the U400M cyclotron at the accelerator complex of the Flerov Laboratory of Nuclear Reactions (FLNR) of the Joint Institute for Nuclear Research (JINR) in 2012. The U400M cyclotron is designed to accelerate ion beams in two modes: in the energy ranges of 19-52 and of 6-9 MeV/u. Using this feature, two dedicated beam lines with low and high energy modes were created and successfully lunched.

Testing was carried out according to the procedure based on international standards, such as EIA/JESD57 and ESCC25100. The standards apply to ions with energies <10 MeV/u. These standards have the following requirements to the ion beam: set of ions with different LET values in the material of tested devices should be used in the tests. There should be no impurities of other atoms in the irradiating ion beams. In this case it is impossible to clean out the ion beam of impurities, a minor presence of impurities is allowed, and their content must be known. It is required by the standards that the LET be known with an accuracy no worse than ±10%. Based on this, the energy of the ions must be measured with the same accuracy. The accepted method of SEE testing requires measurements of ion flux in the range from 1 to 10^5 ions (cm^{-2} s^{-1}), ion fluence up to 10^7 ions/cm^2, beam uniformity at the DUT, and energy of ions.

DC 140 PROJECT

From the common user's requirements, operation simplicity and cost reasons the main parameters of future machine were chosen. The facility will be based on new DC140 isochronous cyclotron: multiparticle, double - energy machine, capable with light and heavy ions up to bismuth (2 and 4.8 MeV/u).

The research works on radiation physics, radiation resistance of materials and the production of track membranes will be carrying out by using the ion beams with energy of about 2 MeV per unit mass and A/Z ratio in the range from 7.58 to 8.0. Besides these, testing of avionics and space electronics by using of ion beams (^{20}Ne, ^{40}Ar, ^{84,86}Kr, ^{132}Xe, ^{197}Au or ^{209}Bi) with energy of 4.8 MeV/u and with mass-to-charge ratio A/Z in the range from 5.0 to 5.5, will be proceeded. One of the significant requirements for this application is the “ion cocktail” means mixed of highly charged heavy ions with the same or very close mass/charge ratios produced and injected in the same time. Once the ions will be accelerated, the different species will be separated by the fine tuning of the cyclotron magnetic field. This issue allows switching the type of ions quick and will reduce the time which user should spend for full scale testing of its samples.

The idea is to effectively use existing stuff to modernize and totally upgrade the old U200 machine which was decommissioned in 2013, because of being outdated

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-FRB02

physically and technologically. The design will be based on existing systems of IC100 and U200 cyclotrons.

The working diagram of DC140 cyclotron is shown in Fig. 1. The acceleration of ion beam in the cyclotron will be performed at constant frequency f = 8.632 MHz of the RF-accelerating system for two different harmonic numbers h. The harmonic number h = 2 corresponds to the ion beam energy W = 4.8 MeV/u and value h = 3 corresponds to W = 2.877 MeV/u. The intensity of the accelerated ions will be about 1 pμA for lighter ions (A < 86) and about 0.1 pμA for heavier ions (A < 132).

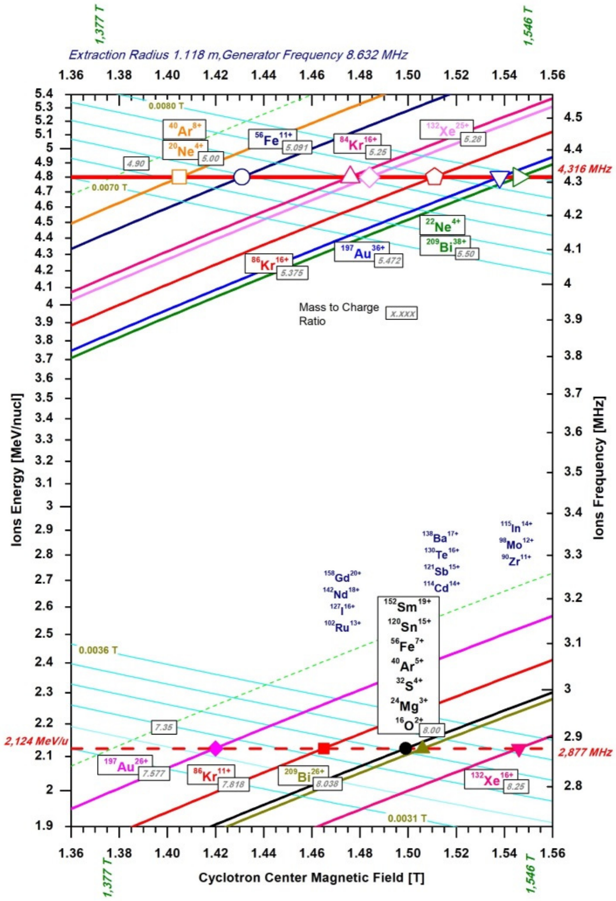

Figure 1: Working diagram of DC140 cyclotron with ^{209}Bi.

The axial injection system and its beam line for new accelerator will be adapted from the existing IC100 cyclotron systems.

In the frame of reconstruction of U200 to DC140 it is planned to upgrade the cyclotron magnetic structure, replace the magnet main coil and renovate RF system. Other systems: beam extraction, vacuum, cooling, control electronics and radiation safety will be new.

EXPERIMENTAL BEAM LINES

The set of the experimental beam lines will include track membrane line; SEE testing line and radiation physics line. The scheme of the experimental beam lines is shown in Fig. 2. The common part of the channel consists of extraction bending magnet, the quadrupole lens triplet and commutating magnet. The centre of the extraction bending magnet is an object point for all beam line. These beam lines will consist of standard subsystems: ion beam transportation system, beam scanning system, beam monitoring system, energy measurement system and user's vacuum test chamber with a mounting, positioning and moving assembly to hold or move the sample in the irradiation field. The experience of working at U400, U400M cyclotrons and existing FLNR apply science facilities will be used during developing the experimental channels for these applications.

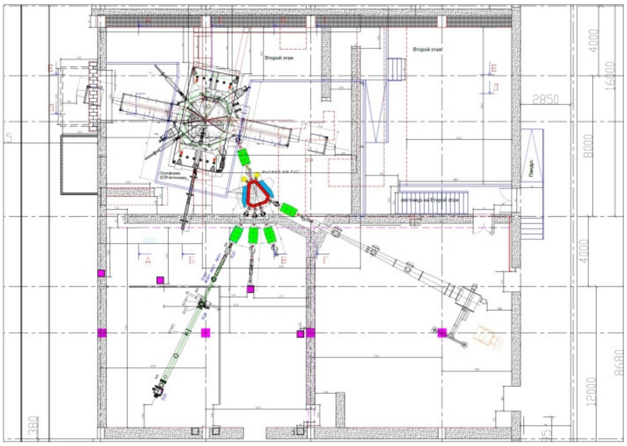

Figure 2: DC140 cyclotron – layout of its casemate and general beam lines overview.

CONCLUSIONS

At present time, Flerov Laboratory of Nuclear Reaction begins the works under the conceptual design of the dedicated applied science facility based on the new DC140 cyclotron. The main characteristics of the new DC140 cyclotron are defined and fit main user requirements well. This dedicated facility is intended for track pore membranes production; SEE testing and radiation materials science. The detailed technical project and the costs estimation will be ready in December 2019. The project is planned to be realised in 2020 - 2022 and will provide the first beam for users before 2023.