

**Federal State Autonomous Educational Institution of Higher Education "Moscow
Institute of Physics and Technology
(National Research University)"**

APPROVED
**Head of Landau Phystech-School of
Physics & Research**
A.V. Rogachev

Work program of the course (training module)

course: Basics of Synchrotron Radiation and Its Applications/Основы синхротронного излучения и его применения
major: Applied Mathematics and Physics
specialization: General and Applied Physics/Общая и прикладная физика
Landau Phystech-School of Physics & Research
Chair of Biophysics
term: 1
qualification: Master

Semester, form of interim assessment: 1 (fall) - Exam

Academic hours: 45 AH in total, including:

lectures: 30 AH.

seminars: 15 AH.

laboratory practical: 0 AH.

Independent work: 60 AH.

Exam preparation: 30 AH.

In total: 135 AH, credits in total: 3

Author of the program: I.V. Manukhov, doctor of biological sciences

The program was discussed at the Chair of Biophysics 04.04.2022

Annotation

A feature of the course is its focus on students who have not previously specialized in the fields of physics directly related to synchrotron radiation. This course will be most useful for those who are planning to use the capabilities of synchrotron radiation as a user, and also (in combination with more advanced courses) to take part in the creation and operation of user stations on SR sources.

1. Study objective

Purpose of the course

The objective of the course is to form understanding of the basic physical principles of synchrotron radiation (SR) generation and use in the fields of biology, medicine, chemistry, geology, materials science, archeology, etc., including the unique opportunities, provided by the latest generations of SR sources. The final part of the course touches on the use of radiation from free electron lasers (FEL).

Tasks of the course

- 1) Acquaintance of students with the basic physical principles of the generation and use of SR in the fields of biology, medicine, chemistry, geology, materials science, archeology
- 2) Acquaintance of students with the unique opportunities provided by the latest generation of SR sources
- 3) Acquaintance of students with FEL.

2. List of the planned results of the course (training module), correlated with the planned results of the mastering the educational program

Mastering the discipline is aimed at the formation of the following competencies:

Code and the name of the competence	Competency indicators
UC-1 Use a systematic approach to critically analyze a problem, and develop an action plan	UC-1.1 Systematically analyze the problem situation, identify its components and the relations between them
	UC-1.2 Search for solutions by using available sources
	UC-1.3 Develop a step-by-step strategy for achieving a goal, foresee the result of each step, evaluate the overall impact on the planned activity and its participants
Gen.Pro.C-1 Gain fundamental scientific knowledge in the field of physical and mathematical sciences	Gen.Pro.C-1.1 Apply fundamental scientific knowledge in the field of physical and mathematical sciences
	Gen.Pro.C-1.2 Consolidate and critically assess professional experience and research findings
Gen.Pro.C-2 Acquire an understanding of current scientific and technological challenges in professional settings, and scientifically formulate professional objectives	Gen.Pro.C-2.1 Assess the current state of mathematical research within professional settings
	Gen.Pro.C-2.2 Assess the relevance and practical importance of research in professional settings
	Gen.Pro.C-2.3 Understand professional terminology used in modern scientific and technical literature and present scientific results in oral and written form within professional communication
Gen.Pro.C-3 Select and/or develop approaches to professional problem-solving with consideration to the limitations and specifics of different solution methods	Gen.Pro.C-3.1 Analyze problems, plan research strategy to achieve solution(s), propose, and combine solution approaches
	Gen.Pro.C-3.2 Employ research methods to solve new problems and apply knowledge from various fields of science (technology)
	Gen.Pro.C-3.3 Gain knowledge of analytical and computational methods of problem-solving, understand the limitations of the implementation of the obtained solutions in practice
Gen.Pro.C-4 Successfully perform a task	Gen.Pro.C-4.1 Apply ICT knowledge and skills to find and study scientific literature and use software products

Gen.Pro.C-4 Successfully perform a task, analyze the results, and present conclusions, apply knowledge and skills in the field of physical and mathematical sciences and ICTs	Gen.Pro.C-4.2 Apply knowledge in the field of physical and mathematical sciences to solve problems, make conclusions, and evaluate the obtained results
	Gen.Pro.C-4.3 Justify the chosen method of scientific research
Pro.C-1 Assign, formalize, and solve tasks, develop and research mathematical models of the studied phenomena and processes, systematically analyze scientific problems and obtain new scientific results	Pro.C-1.1 Locate, analyze, and summarize information on current research findings within the subject area
	Pro.C-1.3 Apply theoretical and/or experimental research methods to a specific scientific task and interpret the obtained results
Pro.C-3 Use research and testing equipment (devices and installations, specialized software) in a selected subject field	Pro.C-3.1 Understand the operating principles of the equipment and specialized software
	Pro.C-3.3 Evaluate the accuracy of the experimental (numerical) results

3. List of the planned results of the course (training module)

As a result of studying the course the student should:

know:

1. Basic physical principles of SR generation and use in the fields of biology, medicine, chemistry, geology, materials science, archeology
2. Unique opportunities provided by the latest generation of SR sources
3. Basics of FEL

be able to:

- 1) Apply knowledge about the physical principles of the generation and use of SR for solving fundamental professional problems;
- 2) Creatively use in scientific activity the knowledge about the unique opportunities provided by the latest generation of SR sources;
- 3) Highlight and systematize the main ideas in scientific texts;
- 4) Critically evaluate any incoming information, regardless of the source;
- 5) Generate new ideas and methodological solutions;
- 6) Carry out the design of their scientific activities;
- 7) Present your scientific results in oral reports.

master:

- 1) Methods of theoretical and experimental research;
- 2) Skills of search (including using information systems and databases), processing, analysis and systematization of information;
- 3) Skills of critical analysis and assessment of modern scientific achievements.

4. Content of the course (training module), structured by topics (sections), indicating the number of allocated academic hours and types of training sessions

4.1. The sections of the course (training module) and the complexity of the types of training sessions

№	Topic (section) of the course	Types of training sessions, including independent work			
		Lectures	Seminars	Laboratory practical	Independent work
1	Introduction	2	1		4
2	Properties of probe beams	2	1		4
3	Interaction of electromagnetic radiation with matter – 1	4	2		8
4	Interaction of electromagnetic radiation with matter – 2	4	2		8
5	Interaction of electromagnetic radiation with matter – 3	4	2		8

6	Basics of modern X-ray imaging and microscopy techniques	2	1		4
7	Basics of modern X-ray scattering and diffraction techniques	2	1		4
8	Basics of modern X-ray spectroscopy techniques	2	1		4
9	Nature of synchrotron radiation	2	1		4
10	Insertion devices	2	1		4
11	Beamlines	2	1		4
12	X-ray free electron lasers	2	1		4
AH in total		30	15		60
Exam preparation		30 AH.			
Total complexity		135 AH., credits in total 3			

4.2. Content of the course (training module), structured by topics (sections)

Semester: 1 (Fall)

1. Introduction

Current progress in study of micro-, nano- and atomic structure of matter. Imaging, diffraction and spectroscopic approaches using electromagnetic radiation, electrons and neutrons as a probe. Resolution limits.

2. Properties of probe beams

Geometrical properties of probe beams: source size, divergence, cross-section, emittance. Flux, flux density and brightness. Spectral flux density. Wave properties of electromagnetic radiation beams, diffraction limit and coherence.

3. Interaction of electromagnetic radiation with matter – 1

Elastic (coherent) scattering of electromagnetic radiation by electron: Thomson and Rayleigh approximations, complex scattering factor, resonant (anomalous) scattering, scattering cross-section.

4. Interaction of electromagnetic radiation with matter – 2

Elastic scattering by atom, molecule, crystal and disordered matter. Refraction and reflection as elastic scattering phenomena, complex refractive index. Scattering from inhomogeneous media. Refraction and reflection in X-ray range.

5. Interaction of electromagnetic radiation with matter – 3

Absorption of X-rays and related processes (Auger, X-ray fluorescence), absorption cross-section. Inelastic scattering: Compton and Raman.

6. Basics of modern X-ray imaging and microscopy techniques

Principles of X-ray imaging optics. Optical resolution limits. Absorption and phase contrast. Photon statistics and resolution limits imposed by absorbed dose. K-edge subtraction imaging, soft X-ray imaging, tomography.

7. Basics of modern X-ray scattering and diffraction techniques

Principles of small-angle scattering and reflectometry. Wide-angle scattering from crystalline and disordered matter. Resonant techniques. Diffraction (lensless) microscopy and the problem of single-molecule imaging. Correlation techniques.

8. Basics of modern X-ray spectroscopy techniques

Principles of soft and hard X-ray spectroscopy. Inelastic scattering spectroscopy. Combination of spectroscopic and imaging/diffraction techniques.

9. Nature of synchrotron radiation

Limitations of laboratory X-ray sources. Use of relativistic particles for X-ray generation. Cyclotron and synchrotron radiation. Bending magnet spectrum. Technical aspects of particle accelerators, time structure of synchrotron radiation for storage ring.

10. Insertion devices

Shifters, wigglers and undulators. Spectral and geometrical properties of undulator radiation. Effect of electron beam emittance, „diffraction limited“ storage rings. Wiggler regime.

11. Beamlines

Beam conditioning: filters, slits, reflective, refractive and diffraction X-ray optical elements. Beam monitors. X-ray detectors.

12. X-ray free electron lasers

Synchrotron radiation from ensemble of electrons. Slicing and self-amplified spontaneous emission. Time structure of synchrotron radiation for XFEL. Applications: time resolved studies, ‘diffraction before destruction’ regime, use of coherence.

5. Description of the material and technical facilities that are necessary for the implementation of the educational process of the course (training module)

1. Classroom with a media projector and screen, Internet access.
2. Required software.
3. Providing independent work - databases on logs.

6. List of the main and additional literature, that is necessary for the course (training module) mastering

Main literature

1. Willmott, Phil. An Introduction to Synchrotron Radiation: Techniques and Applications. Second edition. Hoboken, New Jersey: John Wiley & Sons, Inc, 2019.
2. Als-Nielsen, Jens, and Des McMorrow. Elements of Modern X-Ray Physics. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2011. <https://doi.org/10.1002/9781119998365>.

Additional literature

1. Jacobsen, Chris J. X-Ray Microscopy. Advances in Microscopy and Microanalysis. Cambridge ; New York, NY: Cambridge University Press, 2020.

7. List of web resources that are necessary for the course (training module) mastering

https://henke.lbl.gov/optical_constants/,
<https://xdb.lbl.gov/>

8. List of information technologies used for implementation of the educational process, including a list of software and information reference systems (if necessary)

When preparing and conducting lectures, the Internet is used.

In addition, Libre Office is used, as well as the Ink Scape graphics package.

9. Guidelines for students to master the course

A student studying the discipline must, on the one hand, master the general conceptual apparatus, and on the other hand, must learn to apply theoretical knowledge in practice.

As a result of studying the discipline, the student must know the basic definitions and concepts, be able to apply the knowledge gained to solve various problems.

Successful completion of the course requires:

- attendance of all classes provided for by the curriculum for the discipline;
- keeping a synopsis of classes;
- student's intense independent work.

Independent work includes:

- reading recommended literature;
- study of educational material, preparation of answers to questions intended for independent study;
- solving problems offered to students in the classroom;
- preparation for the performance of tasks of the intermediate certification.

An indicator of mastery of the material is the ability to answer questions on the topics of the discipline without a synopsis.

It is important to achieve an understanding of the material being studied, not its mechanical memorization. If a student finds it difficult to study certain topics, questions, he/she should seek advice from a teacher.

Intermediate control of students' knowledge is possible in the form of solving problems in accordance with the topic of classes.

Assessment funds for course (training module)

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Chair of Biophysics
term: 1
qualification: Master

Semester, form of interim assessment: 1 (fall) - Exam

Author: I.V. Manukhov, doctor of biological sciences

1. Competencies formed during the process of studying the course

Code and the name of the competence	Competency indicators
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2. Competency assessment indicators

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master:

- 1) Methods of theoretical and experimental research;
- 2) Skills of search (including using information systems and databases), processing, analysis and systematization of information;
- 3) Skills of critical analysis and assessment of modern scientific achievements.

3. List of typical control tasks used to evaluate knowledge and skills

Not provided.

4. Evaluation criteria

Checking questions and tasks:

1. Before the reconstruction of 2019, the size of the radiation source for photons with an energy of 10 keV at the experimental stations of the European Synchrotron Radiation Center (ESRF) in Grenoble (France) was $412 \times 6 \mu\text{m}$ r.m.s. (horizontally and vertically, respectively), and the divergence was $12 \times 5 \text{ mrad}$ r.m.s. After the reconstruction, these values have decreased to $28 \times 6 \mu\text{m}$ and $7 \times 5 \text{ mrad}$. Calculate the degree of beam coherence (in the vertical and horizontal planes) at 10 keV before and after reconstruction.
2. Plot the reflectivity curve of the vacuum-silicon interface for 10 keV X-rays.
3. Estimate the photon flux corresponding to the main types of interaction of radiation with matter if the incident 10^{10} photons/s flux of 10 keV photons falls on a diamond nanoparticle with a diameter of 100 nm.
4. Cell organelles differ in the ratio of water and organic matter. Can be X-ray microscopy of cell structure based on absorption contrast effective?
5. Estimate number of incident photons necessary to solve average protein structure in the regime of 'single molecule diffraction' and in the conventional MX experiment with $10 \times 10 \times 10$ microns sample.
6. To what relative spectral width is it sufficient to monochromatize radiation with an energy of 10 keV in order to study elastic vibrations (phonons) with an energy of ~ 0.01 eV in a sample?
7. A 16-bunch mode is used to study fast processes at the storage ring with perimeter of 476 m (a synchrotron radiation pulse from a single bunch is used to record one image/scattering pattern/spectrum). Calculate time resolution (in frames per second) of the resulting 'movie'.
8. Resonance scattering by heavy atoms (Se, Br) integrated into the protein is often used for phasing. What is the minimum amplitude of the magnetic field that must be created in an undulator with a period of 2 cm in order to use resonance scattering at the K edge of selenium? The energy of electrons in the storage ring is 3 GeV.
9. Calculate the focal length of a compound refractive X-ray lens, which consists of 30 holes with a radius of 0.3 mm in an aluminum block for radiation with an energy of 14 keV.
10. How many orders of magnitude will differ intensity of SR emitted by an electron bunch of 1 nC in the undulator of the storage ring and in the undulator of the free electron laser? Consider the energy of electrons and the parameters of undulators to be the same.

Examples of exam question papers:

Question paper 1

1. Before the reconstruction of 2019, the size of the radiation source for photons with an energy of 10 keV at the experimental stations of the European Synchrotron Radiation Center (ESRF) in Grenoble (France) was $412 \times 6 \mu\text{m}$ r.m.s. (horizontally and vertically, respectively), and the divergence was $12 \times 5 \text{ mrad}$ r.m.s. After the reconstruction, these values have decreased to $28 \times 6 \mu\text{m}$ and $7 \times 5 \text{ mrad}$. Calculate the degree of beam coherence (in the vertical and horizontal planes) at 10 keV before and after reconstruction.

2. Plot the reflectivity curve of the vacuum-silicon interface for 10 keV X-rays.

Question paper 2

1. Estimate the photon flux corresponding to the main types of interaction of radiation with matter if the incident 10^{10} photons/s flux of 10 keV photons falls on a diamond nanoparticle with a diameter of 100 nm.

2. Cell organelles differ in the ratio of water and organic matter. Can be X-ray microscopy of cell structure based on absorption contrast effective?

Assessment “excellent (10)” is given to a student who has displayed comprehensive, systematic and deep knowledge of the educational program material, has independently performed all the tasks stipulated by the program, has deeply studied the basic and additional literature recommended by the program, has been actively working in the classroom, and understands the basic scientific concepts on studied discipline, who showed creativity and scientific approach in understanding and presenting educational program material, whose answer is characterized by using rich and adequate terms, and by the consistent and logical presentation of the material;

Assessment “excellent (9)” is given to a student who has displayed comprehensive, systematic knowledge of the educational program material, has independently performed all the tasks provided by the program, has deeply mastered the basic literature and is familiar with the additional literature recommended by the program, has been actively working in the classroom, has shown the systematic nature of knowledge on discipline sufficient for further study, as well as the ability to amplify it on one’s own, whose answer is distinguished by the accuracy of the terms used, and the presentation of the material in it is consistent and logical;

Assessment “excellent (8)” is given to a student who has displayed complete knowledge of the educational program material, does not allow significant inaccuracies in his answer, has independently performed all the tasks stipulated by the program, studied the basic literature recommended by the program, worked actively in the classroom, showed systematic character of his knowledge of the discipline, which is sufficient for further study, as well as the ability to amplify it on his own;

Assessment “good (7)” is given to a student who has displayed a sufficiently complete knowledge of the educational program material, does not allow significant inaccuracies in the answer, has independently performed all the tasks provided by the program, studied the basic literature recommended by the program, worked actively in the classroom, showed systematic character of his knowledge of the discipline, which is sufficient for further study, as well as the ability to amplify it on his own;

Assessment “good (6)” is given to a student who has displayed a sufficiently complete knowledge of the educational program material, does not allow significant inaccuracies in his answer, has independently carried out the main tasks stipulated by the program, studied the basic literature recommended by the program, showed systematic character of his knowledge of the discipline, which is sufficient for further study;

Assessment “good (5)” is given to a student who has displayed knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, who while not being sufficiently active in the classroom, has nevertheless independently carried out the main tasks stipulated by the program, mastered the basic literature recommended by the program, made some errors in their implementation and in his answer during the test, but has the necessary knowledge for correcting these errors by himself;

Assessment “satisfactory (4)” is given to a student who has discovered knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, who while not being sufficiently active in the classroom, has nevertheless independently carried out the main tasks stipulated by the program, learned the main literature but allowed some errors in their implementation and in his answer during the test, but has the necessary knowledge for correcting these errors under the guidance of a teacher;

Assessment “satisfactory (3)” is given to a student who has displayed knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, not showed activity in the classroom, independently fulfilled the main tasks envisaged by the program, but allowed errors in their implementation and in the answer during the test, but possessing necessary knowledge for elimination under the guidance of the teacher of the most essential errors;

Assessment “unsatisfactory (2)” is given to a student who showed gaps in knowledge or lack of knowledge on a significant part of the basic educational program material, who has not performed independently the main tasks demanded by the program, made fundamental errors in the fulfillment of the tasks stipulated by the program, who is not able to continue his studies or start professional activities without additional training in the discipline in question;

Assessment “unsatisfactory (1)” is given to a student when there is no answer (refusal to answer), or when the submitted answer does not correspond at all to the essence of the questions contained in the task.

5. Methodological materials defining the procedures for the assessment of knowledge, skills, abilities and/or experience

The course is graded at an exam. The questioning starts with a random task assigned to each student and time given for completion of the task. No aids are allowed. The student then proceeds to a chat with the examiner, at which he/she presents his/her solution to the assigned task. The examiner then asks the student several questions that evenly cover the course content. A final grade is assigned based on the quality of answers and demonstrated level of understanding.