BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS

Doctoral School of Physical Sciences

Training Programme
2020

Contents:

Preamble

The Training Programme has been prepared considering the applicable regulations and the regulations of BME, in particular the Act CCIV of 2011 on National Higher Education (hereinafter: NHEA), the Gov. Decree 387/2012 (XII.19.) on doctoral schools, doctoral procedures and habilitation, as well as the Doctoral and Habilitation Procedures of BME (BME DHSZ) and the Academic and Examination Regulations of BME (BME TVSZ).

Where the Training Programme's requirements are not stipulated in the above regulations or exceed them, those requirements can – in exceptional cases – be reduced to the lowest acceptable level established in the higher level regulation. The permission shall be granted (on a substantiated written request) by the DIT (for doctoral trainings) or the HBDT (for degree award procedures). The decision on the request shall be protocolled.

I. COMPONENTS OF THE PHD PROGRAMME

The most important component of the doctoral programme are the independent research activities completed in the research topics announced by the Doctoral School. Each doctoral student is assigned one and only one supervisor, who have full responsibility in guiding and helping the academic and research work of the doctoral student working on the topic, and also the publication of results and the completion of the doctoral theses. The dual supervisory system is only allowed – and then requires the involvement of a co-supervisor – in the case of international co-operations, or in the case of interdisciplinary topics, if the topic was approved by the Council of the Doctoral School (DIT) and the topic announcement was made on the prior consent from the Habilitation Committee and Doctoral Council of the University (EHBDT). If the supervisor is an invited person or external to the University, the Council of the Doctoral School (DIT) appoints an internal consultant to support the supervisor's work and to monitor the professional progress of the student.

Throughout the doctoral programme, the students may choose MSc or PhD subjects additionally to the doctoral subjects announced for the particular semester – even from the curriculum of an other university – that are accepted and credited by the Council of the Doctoral School. The curriculum is further expanded by the lectures held in English by lecturers invited for particular semesters, and the mutual cross-learning agreement with Eötvös Lóránd University. Credits acquired for attending subjects are grouped for the first 4 semesters of the two-staged programme. International activities during the last 4 semesters and related skill developments are recognized with the curriculum credit points granted for attending international intensive courses, thematic "summer schools" (winter schools) on condition the participation is certified, and is supported by the supervisor.

Teaching under guidance is part of the training, where students deepen their competence in the subject and improve their abilities to develop learning materials, present and communicate under the guidance of a designated lecturer. The subject and the related credits shall be selected by the head of the supervisor's or the consultant's department – in agreement with the supervisor. The completion of the subject shall be approved and evaluated with grades by the head of department based on the opinion of the lecturer responsible for the subject. Any lecturing activity beyond those prescribed for the doctoral training should be paid according to Section 179 of the Academic and Examination Regulations of BME.

The tutorial nature of the training is emphasized by the regular consultation where participation is recognized by credit points, as well as the support of research and publication activities. The competence of students and their activities at consultation shall be evaluated with ***consultation credit*** by the supervisor in each semester. The progress in time in the doctoral topic shall be recognized with specific ***research credit***. ***Publication credit*** can be conferred for the publication of novel results in international journals or for presenting them at an international conference, considering the preparatory work, too (i.e. acceptance/publication is not required). The students shall compile an article independently to be published in the Doctoral School's self-edited publication to show their achievements during the first year.

By proposing credits for publication activities, the supervisor indicates to the DIT that by acquiring all publication credit points before the end of the fourth semester, the student meets the precondition to be admitted to the complex examination, and similarly, by the end of the eight semester, the minimum requirement for acquiring a degree is met. The research credits proposed by the supervisor shall be approved semi-annually by the DIT. To establish the credits, the DIT may seek out the opinion of the doctoral topic owner (i.e. the department of the supervisor/consultant).

Progress and academic performance of students shall be evaluated by the DIT in each academic year. As part of the yearly evaluation of research performance, the results achieved during the reporting period shall be presented in a lecture form delivered at a PhD professional day. The credits proposed by the supervisor shall be approved by the DIT based on the lecture and the professional report on the two semesters’ achievements.

II. PROFESSIONAL COMPETENCIES TO BE ACQUIRED

Our goal is that a physicist holding a PhD degree possess the competencies detailed below.

a) knowledge

Knows the general laws of physics at system level and in various relationships.

Acquired in depth (researcher level) knowledge of the subject, general and specific characteristics, major trends and limits, and the relationships – both settled and disputed ones – of his/her discipline.

Has solid knowledge on the most important relationships, theories and underlying concepts and nomenclature (terminology) of the natural sciences disciplines closely related to the student's own scientific discipline.

Adapts an analytic and understanding approach while continually contributing to the fiducial knowledge in the international literature.

Acquired the required level of knowledge in informatics and mathematics to creatively apply them to manage, evaluate and publish his/her own research data and results.

Acquired the research methodology knowledge required for individually conducting research his/her own discipline.

Acquired in depth knowledge and understands the relationships, theories and underlying concepts and nomenclature required by their creative application.

b) skills and capabilities

Apt to recognize the physical laws beyond the natural phenomena, experimentally study and theoretically interpret them in a scholarlike way.

Apt to independently plan and implement new projects and work phases in his/her discipline.

Capable of performing creative analyses within his/her own discipline, formulating and modelling comprehensive and specific relationships in a novel, synthetic way, and performing evaluations and criticism.

Apt to apply and improve the learning and problem solving methods characteristic of his/her discipline.

Apt to creatively develop novel and previously unknown methods for the practical application of questions of principle.

Capable of recognizing professional issues in his/her field, and is able to explore the theoretical and practical background at the research level in such details required for solving them.

Apt to creatively connect information from unrelated or loosely connected fields and explore inherent relationships between them. Meanwhile, the student is capable of recognizing and highlighting significant and crucial aspects in the creative process of evaluating the research results.

Apt to realistically and critically analyse and evaluate his/her own as well as others' results on strictly professional ground and treat them according to their true vale.

Apt to critically handle physics related information and news, and contributes to professional disputes with arguments based on expertise.

Apt to transfer knowledge at the adequate level both to professionals of his/her own field and to the average laymen, and to participate in professional arguments and discussions.

Capable of oral and written expert communication and professional cooperation both in domestic and international relations.

Capable of summarizing, presenting and transferring his/her knowledge and research achievements in his/her academic discipline. The student is familiar with the regular publication methods of his/her field and is capable of practicing them on his/her own (e.g. independent authoring of articles, books, academic works).

c) attitude

S/he is creative, flexible and intuitive, works systematically, possesses good data processing, decision making, and problem identification and solving skills.

Strives to identify and conceptualize scientific problems yet unexplored and unsolved.

Has a strong professional commitment and accepts the need for persistent work.

Open to learn new technologies and newly developing research areas, to convey the acquired knowledge and to embed fiducial elements into his/her own research and development activity and further develop them.

S/he thinks open-minded and exempt from professional preconceptions in the course of problem solving and model creation.

Realistically and yet emphatically evaluates professional achievements and performances pertaining to his/her own and his/her team members' work.

Accepts fair professional critics and other's professional arguments.

Open and committed to participate in professional cooperation or initiate them both in domestic and international relations.

S/he is continuously striving for an efficient balance between individual and team work.

Pursues his/her professional work independently, immersed but open to team work and to support other's work.

d) autonomy and responsibility

Capable of elaborating comprehensive and special professional problems, representing professional opinions and arguing for them autonomously in the field of modern physics.

Consciously and responsibly takes on the scientific view of the world.

Responsibly assumes answering the ethical matters evolving in connection with theoretical and practical issues of his/her profession.

As research leader, s/he can steer the activity of his/her colleagues through independent decisions and takes responsibility for ensuring their professional development.

S/he takes a peer discussion partner role in disputes with professionals in his/her own scientific discipline.

All his/her activities are determined by an expertise-based responsible thinking for the preservation of living and inanimate nature and for the improvement of their condition.

S/he can creatively build new knowledge areas autonomously, and initiates novel practical solutions.

III. MODEL CURRICULUM

Subject/type	**Total credits**	1. semester	2. semester	3. semester	4. semester	5. semester	6. semester	7. semester	8. semester
Curriculum material 24									
Subject / KV	18	4/v/6	4/v/6	2/v/3	2/v/3				
Summer school /V	6						3		3
Teaching under guidance 18									
Teaching /K	18	2/f/3	2/f/3	2/f/3	2/f/3	2/f/3	2/f/3		
Research 144									
Consultation /K	48	6/f/6	6/f/6	6/f/6	6/f/6	6/f/6	6/f/6	6/f/6	6/f/6
Research work	96	12	12	12	12	12	12	12	12
Publication 54									
Publication /K	48	3	3	6	6	6	6	9	9
Conferences /V	6					3		3	
Total:	***240***	***30***	***30***	***30***	***30***	***30***	***30***	***30***	***30***

Students must earn 240 credit points during the training. Credit limits for the various activities:

Curriculum material	18–30 credit points
Teaching under guidance	18–24 credit points
Research work	120–150 credit points
Publications	54–66 credit points

The doctoral candidate must complete no less then 15 credits during the active semester, otherwise his/her legal relationship with the BME shall be terminated (Section 186 (2) of the BME TVSZ).

Students funded through Hungarian state scholarship may be reallocated into private-funded status by the Dean's decision upon recommendation from the DIT, if they do not complete minimum 20 credits during the active semester (Section 13 (8) of the BME DHSZ).

Students with private-funded status may be reallocated into state-funded status by their request on condition the DIT's opinion is supportive (for details see Section 13 (8) of the DHSZ).

If a student submits his/her doctoral dissertation any time during the second phase of the programme, and the Habilitation Committee and Doctoral Council (HBDT) enters it for the critique procedure, the research and the publication credits completed during a given semester shall be recognized. Students who satisfied every academic and examination requirements prescribed in the curriculum, furthermore earned 240 credits shall obtain the pre-degree (final) certificate (absolutorium), whereas their legal relationship – and the eligibility for stipend in the case of students who pursue state-financed studies – with the BME shall remain until the last day of the semester (Section 59 (1/d) of the NHEA).

IV. COMPREHENSIVE EXAMINATION

The Council of the Doctoral School shall decide on the admittance to the comprehensive examination. Students are only allowed to take the exam if they earn at least 90 credits during the first four semesters, and all **subject credits** prescribed in the model curriculum of the doctoral school (except for students preparing individually for acquiring the doctoral degree, whose legal relationship with the university will be established by the registration for and admittance to the comprehensive examination).

The publication related condition for admittance to exam is the publication - or accepted or submitted for publication – of at least **one** scientific publication in a “Web of Science” qualified journal, or a scientific publication electronically published in arXiv (lanl.gov), furthermore, the verification of at least **one** lecture or poster presented at a conference. Formal compliance with this requirement does not automatically guarantee admittance to exam; the DIT substantially verifies the level of publication of scientific results, and also the candidate’s contribution to the published results.

In the case of students preparing individually, the precondition for being admitted to the exam is formal compliance with the publication and language requirements of acquiring the doctoral degree (no thesis points are required at the time of registration, therefore, instead of the substantial evaluation, only expected numerical indicators have to be met).

Comprehensive exam has to be taken in public, before the Committee. The examination committee consists of at least three members, and minimum of one third of the members shall have no employment relationship with the institution operating the Doctoral School. The chair of the examination committee is a university professor, *or a* Professor Emeritus, *or* a lecturer, researcher with Doctor of the MTA title. Each member of the examination committee should have scientific degree. The supervisor of the examinee cannot be a member of the Committee. The supervisor shall deliver the supervisory assessment of the student’s performance to the chair of the committee in electronic form at least one week before the set date of the exam. The supervisor shall be invited to the comprehensive examination.

The comprehensive examination is divided into two parts: one part assesses the theoretical competence of the student (“theoretical part”), whereas in the “thesis part” the examinees can prove their scientific progress.

During the theoretical part, the examinee takes exam in two subjects. In this part the complex examination committee also evaluates the candidate's knowledge of the literature and of the theoretical foundations of the research field. The list of subject is included with the curriculum of the doctoral school, and is accessible on the webpage of the doctoral school. In the theoretical part of the exam, the doctoral students demonstrate their awareness of literature in the specific branch of science, and their current knowledge in theory and methodology.

In the other part of the comprehensive exam, the examinees provide an account of their awareness of literature in their research topic (in a presentation form), report their research results, present the research schedule for the second part of the doctoral programme, as well as the schedule of the thesis preparation and the publication of results. The presentation will also review the scientific importance and innovation value of the results, and - where applicable – the technology motivation behind the research, and practical applicability of the results. At least one week before the exam, the examinee submit a brief summary of results achieved to date to the committee, together with the papers published or sent for publication. Each member of the examination committee shall assess the theoretical and thesis part one-by-one, separate. The comprehensive exam will be qualified successful, if the simple majority of the committee members decide so regarding both parts of the exam. The doctoral student may retake a failed comprehensive exam on one occasion, within the same exam period.

Minutes including textual assessment shall be drawn up on the comprehensive examination.

The outcome of the exam shall be announced on the exam day. The result of the comprehensive exam does not count in the qualification of the doctoral degree, but the successful completion is a precondition of being admitted into the second stage of the programme.

Subjects of the comprehensive examination

PHYSICS

Condensed matter physics

1. Electrons in solids
2. Semiconductors
3. Magnetism
4. Superconductivity
5. Material characterization methods

Optics

6. Models of light
7. Optical and photonic devices
8. Laser physics
9. Optical metrology and spectroscopy
10. Optical materials

Statistical physics and thermodynamics

11. Quantum statistical mechanics
12. Non-equilibrium systems and chaotic dynamics
13. Complex systems and game theory
14. Computational methods and simulations
15. Phase transitions

Quantum theory

16. Many-body physics
17. Quantum field theory and particle physics
18. Quantum physics of electron systems
19. Quantum optics and quantum information science
20. Mesoscopic and strongly correlated systems

NUCLEAR TECHNIQUES

Fusion plasma physics

1. Concepts of fusion power generation
2. Magnetic confinement fusion technology
3. Theoretical fusion plasma physics

Medical physics

4. Teletherapy – photon and electron therapy
5. HDR and LDR brachytherapy
6. Medical imaging by ionizing radiation
7. Medical imaging by non-ionizing radiation

Nuclear metrology and radioanalytics

8. Radiation and particle sources
9. Detection of electromagnetic radiation and particles
10. Radioanalytical methods

Radiation protection

11. Radiation protection and its legislation
12. Pollution propagation and radioactive waste management

Nuclear reactor physics

13. Nuclear physics
14. Reactor physics
15. Thermal hydraulics
16. Monte Carlo particle transport methods
17. Nuclear reactors and fuel cycle
18. Operation and maintenance of nuclear reactors
19. Nuclear reactor safety

CONDENSED MATTER PHYSICS SYLLABUS

1. Electrons in solids

Bloch theorem, electronic band structure, metals and semiconductors. Wave packet, quasiclassical dynamics, effective mass.

Ballistic transport, quantized conductance. Mesoscopic transport, Landauer formalism. Macroscopictransport: Boltzmann equation, relaxation time approximation.

2. Semiconductors

Bond structure and band structure of semiconductor crystals. Doping, impurity levels. Transport in pure and doped semiconductors.

Band gaps, band engineering. Two-dimensional electron gas. Quantum Hall effect. Level structure of quantum dots, single-electron transistor.

Modern semiconductor devices: MOSFET, Flash memory, semiconductor laser.

3. Magnetism

Landau levels, magnetic oscillations, experimental determination of the Fermi surface. Magnetic susceptibility of conduction electrons, Stoner enhancement.

Hund’s rules, interaction of magnetic moments in crystal structures, lattice models of magnetism, magnetic ordering. Heisenberg model, ferromagnetism.

Interpretation of ferromagnetism in the band picture, spin-polarized electronic states, spintronics.Magnetic resonance: NMR, ESR.

4. Superconductivity

Phenomenological description of type-I and type-II superconductors. Cooper pairs, BCS theory, macroscopic quantum state. Flux quantization, Josephson effect, SQUID.

Superconducting vortices, Ginzburg–Landau theory of type-II superconductors. High-temperaturesuperconductors, applications of superconductivity.

5. Material characterization methods

Structural characterization by diffraction methods. Electron microscopy (TEM, SEM, electronbeam lithography).

Scanning probe methods (AFM, STM).

Optical investigation of the electronic structure and vibrational modes (Raman and optical spectroscopy, angle-resolved photoemission spectroscopy). Surface analytical methods (SIMS, XPS, AES).

OPTICS SYLLABUS

6. Models of light

Electromagnetic theory of light propagation in homogeneous dielectric and conductive media. Dispersion. Fresnel–Kirchhoff diffraction theory. Light scattering.

Fundamentals of geometrical optics. Properties of optical systems; paraxial, third-order and diffraction approximations for the evaluation of imaging performance. Correction of monochromatic and chromatic aberrations. The process and tools of optical desig

7. Optical and photonic devices

Basic components for imaging: condenser, collimator, achromatic doublet, photographic lens, relay lens, eyepiece, telescope, optical microscope, illumination methods. Photonic devices for the manipulation of intensity, frequency, phase, polarization and direction of light. Waveguides and periodic multilayer structures.

Thermal radiation, incandescent lamps. Gas discharge. Types of gas-discharge lamps and their characteristics. Semiconductor light sources. Semiconductor devices based on photon emission and absorption.

8. Laser physics

Fundamentals of laser operation. Phenomenological theory of the light–matter interaction. Resonators. Description of continuous wave (CW) and pulsed operation, mode-locking. Generation and applications of ultrashort pulses. Laser amplifiers.

Semiclassical laser theory, quantum theory of lasers. Application of lasers in medicine, telecommunications, industry and research.

9. Optical metrology and spectroscopy

Types, operation and properties of photodetectors. Methods and limits of optical power measurement. Interferometry, interferometers. Holography and its applications. Optical shape and distance measurement. Imaging systems in metrology.

Interaction of light and matter in case of atoms, molecules and solids. Absorption, emission, light scattering. Devices for spectral measurements and their properties. Quantities in photometry and radiometry.

10. Optical materials

Crystal optics. Special effects in transparent solids (electro-optic effect, photoelastic effect and acousto-optics, nonlinear and other phenomena). Physical properties of main optical materials.

Properties and materials of optical multilayer structures. Main manufacturing processes of optical materials (glasses, crystals). Manufacturing of bulk optical elements. Fabrication of optical multilayer structures. Patterning, integrated optics.

Fundamentals of nonlinear optics; frequency doubling, parametric amplification, phase conjugation. Importance of frequency and phase matching, and the photon approach.

STATISTICAL PHYSICS AND THERMODYNAMICS SYLLABUS

11. Quantum statistical physics

- Density matrices and density operators. (Neumann equation, equilibrium, entanglement, principle of maximal entropy).
- Quantum gases, Bose-Einstein condensation and superfluidity.
- Correlations and linear response (Kubo formula, fluctuation-dissipation theorem, Kramers-Kronig relation).
- Second quantization.
- Principles of quantum Monte-Carlo methods (Trotter formula, discussion on some simple system).

12. Non-equilibrium systems and chaotic dynamics

- Brownian motion and diffusion (Langevin vs. Fokker-Planck equation).
- Markov processes and relaxation to equilibrium (H-theorem, maximum entropy principle and basic principles of Monte Carlo simulation).
- Pattern formation, and fractal growth, multifractals.
- Ergodicity and classical chaos (dynamical systems, attractors, Lyapunov exponents, integrable vs. non-integrable systems, Hamiltonian systems and Liouville's equation).
- Classically integrable/chaotic systems at the quantum level (Wigner-surmise, Poisson vs. Wigner-Dyson statistics, Gutzwiller's trace formula).

13. Complex systems

- Small world networks vs. Erdős-Rényi model, network growth models.
- Network motifs. Communities. Directed, weighted and signed networks. Spreading. Temporal networks. Social, economic and ecological networks.
- Basic concepts of traditional game theory. Potential games. Evolutionary games.
- Disordered systems: Percolation, basic spin glass properties and models. Fractals and multifractals.

14. Computational methods and phase transitions

- Molecular dynamics. Interactions, solution methods. Event directed MD, instabilities.
- The Monte Carlo method (detailed balance, Metropolis algorithm, importance sampling, averaging) and simulated annealing.
- Second-order phase transitions and universality (critical exponents, critical correlations, scaling laws).
- Wilson's renormalization group concept and its implications (finite size scaling, scaling of free energy).
- Finite size scaling, and critical dynamics (critical slowing down, speed-up techniques).

15. Many-body physics

- Second quantization. Linear response, Green’s functions. Kramers-Kronig relation.
- Perturbation theory and diagrammatic techniques. (Feynmann diagrams, Dyson equations, self-energy). Fermi liquids and non-Fermi liquids.
- Interacting one dimensional fermions (renormalization group and basic properties of Luttinger liquids).
- Electron-phonon interactions (polarons, Peierls transition, Cooper instability).
- Superconductivity, Cooper instability. Mean field theory.
- Interacting bosons, Bogoliubov theory, superfluidity.

16. Quantum field theory and particle physics

- Relativistic fields. Canonical quantisation, spin-statistics and CPT theorem.
- Interacting fields, scattering theory, cross sections. Feynman rules. Functional integral methods. Generating functionals. Path integral for fermions.
- Renormalisation. Classification of divergences, counter terms. φ^4 theory and QED at one loop.
- Renormalisation group, Callan-Symanzik equation. Operator product expansion.
- Symmetries, Ward identities. Spontaneous symmetry breaking. Gauge invariance, elements of non-Abelian gauge theory.
- Weak interactions. Parity and CP violation. Charged current Lagrangian, flavour mixing, neutrino oscillations. $SU(2)_L x U(1)_Y$ gauge theory, Higgs mechanism.
- Strong interactions. SU(3) quark model. Fundamentals of quantum chromodynamics, confinement and asymptotic freedom.

17. Quantum physics of electron systems

- Free electrons in Hartree-Fock approximation. Density functional theory. Extensions of DFT: SDFT, self-interaction correction.
- Variational and pseudopotential methods.
- Point group symmetry in band structure. Time reversal symmetry and spin-orbit coupling.
- Surface states, Bychkov-Rashba effect, symmetry analysis of the effective Hamiltonian.
- Green function method in tight-binding approximation. Band structure of alloys, coherent potential approximation.
- Ab initio theory of itinerant magnetism, Stoner model. Method of disordered local moments.

18. Quantum optics and quantum informatics

- Radiation transitions. Photodetection, photon statistics. Hanbury-Brown and Twiss experiment, photon antibunching. Coherent and squeezed states, Wigner functions.
- Resonant atom-light interaction. Atoms in resonators, Purcell effect, strong coupling.
- Ultracold atoms, Bose condensation, optical lattices.
- Entanglement, Bell inequalities, quantum teleportation, quantum cryptography.
- Quantum computing and quantum algorithms.
- Realisation of q-bits, one and two q-bit operations. Mechanisms of information loss: relaxation, dephasing, decoherence.

19. Quantum theory of mesoscopic systems

- Generic properties of metallic grains (random matrix theory, level repulsion, universality classes).
- Conductance through mesoscopic structures (Landauer-Büttiker formula and conductance quantization, random matrix theory of conductance, quantum Hall edge states, universal conductance fluctuations).
- Coulomb blockade in quantum dots and molecules (spectroscopy, co-tunneling, signatures of Kondo effect).
- Superconducting grains and Josephson junctions. Superconducting Q-bits and their manipulation.
- Anderson localization (mobility edge, scaling theory).

NUCLEAR TECHNIQUES SYLLABUS

FUSION PLASMA PHYSICS

1. Concepts of fusion power generation

Nuclear physics basics for fusion power: reactions, cross sections, fuel cycle, concept of thermonuclear fusion. Comparison of the concepts of peaceful thermonuclear power (inertial and magnetic confinement).

Main types of plasma diagnostics, related physical phenomena: plasma waves, plasma radiation, rate equations. Prominent fusion devices.

2. Magnetic confinement fusion technology

Magnetic confinement, motion of charged particles in a magnetic field. Geometry of the magnetic field in the various designs: linear device, stellarator, tokamak, RFP. Installation and main components of fusion devices. Plasma production, refueling, heating, plasma-wall relationship, current drive, course of an experiment.

Particle and heat transport in fusion plasmas. Instabilities important from the perspective of operation.

3. Theoretical fusion plasma physics

Definition and primary physical properties of a plasma. Formulation, properties and limit of applicability of the kinetic theory, the multi-fluid plasma model and magnetohydrodynamics; examples through applications.

MHD equilibrium, MHD stability, prominent plasma waves and their applications in magnetic confinement fusion devices.

MEDICAL PHYSICS

4. Teletherapy – photon and electron therapy

Principles of operation, design and characteristic parameters of radiotherapy treatment machines. Photon and electron beam calibration, dosimetry of small radiation fields. Devices and methods of metrology used in radiotherapy. Radiation design, the role of imaging, assessment of radiation treatment plans, plan quality indices, patient dosimetry. Equipment of image-guided radiotherapy, correction methods. Radiation protection of teletherapy treatment machines. Radiobiological characteristics of acute and late side effects induced by radiation, LQ model. Prevention of radiation accidents, quality assurance measurements and risk assessment.

5. HDR and LDR brachytherapy

Brachytherapy radiation techniques, properties of radiation sources, characteristics of afterloading treatments. Design, quality assurance and radiation protection of HDR devices, use of applicators. Characteristics, tools and radiation protection of LDR brachytherapy treatments. Role of imaging equipment in therapy. Radiobiology characteristics of HDR és LDR brachytherapy, acute and late side effects. Determination of the organs at risk and the planning target volume, radiation treatment planning techniques, dose prescription, methods of dose calculation. Prevention of radiation accidents, quality assurance measurements and risk assessment.

6. Medical imaging by ionizing radiation

Mathematics and algorithms of tomographic and planar image reconstruction: Radon and inverse Radon transform, ML-EM method, planar imaging procedures and image quality features. Diagnostic x-ray: sources, detectors, CT. Isotope diagnostics: radiation sources, design and detectors of the gamma camera, PET and SPECT, Anger principle, collimators. Parameters affecting image quality. Propagation of ionizing electromagnetic radiation in tissue, Monte Carlo methods with medical applications.

7. Medical imaging by non-ionizing radiation

Magnetic resonance imaging: basic concepts, ordering and relaxation of spins in an external magnetic field, T1 and T2 relaxation, Bloch equations, design and operation of an MRI machine, FID, pulse-echo and IR sequences, 3D MR imaging, effect and correction of chemical shift. EPI sequence, artifacts and their possible correction, dependence of the signal-to-noise ratio on the imaging parameters, noise statistics in real and k-space, contrasts. Parallel imaging techniques. Simultaneous multi-slice imaging, controlled aliasing, phase-constrained imaging, compressed sensing MRI, modern diffusion MRI. Diagnostic ultrasonography: sources and detectors, interaction of ultrasound with matter, tissue models, A-, B- and M-mode imaging, Doppler mode.

NUCLEAR METROLOGY AND RADIOANALYTICS

8. Radiation and particle sources

Phenomena of nuclear and atomic physics. Ion sources, particle acceleration by electrostatic and resonance methods, design and operation principles of linear and circular accelerators, beam handling, ion optics, storage rings, special accelerators for nuclear and atomic physical investigations, high-energy accelerators built for particle physics applications, synchrotrons and free-electron lasers for atomic physics and material structure investigations. Accelerators of prominent particle physics laboratories.

9. Detection of electromagnetic radiation and particles

Principles of detection and the corresponding interactions between electromagnetic radiation and matter, particles and matter. Physical options and technical implementations of the detection of neutrinos and neutrons. Gaseous ionization detectors, scintillators and semiconductor detectors, devices and their applications. Design and primary structural elements of electromagnetic radiation and particle spectrometers. Methods and possible applications of gamma, X-ray, beta and alpha spectrometry, pulse-shaping concepts (pulse shape discrimination, time of flight, coincidence, position sensitive detection, etc.) and electronic methods. Special semiconductor, superconductor and dosimetric detectors.

10. Radioanalytical methods

Principles of radioanalytics, its primary technical procedures, and its applications for the investigation of the chemical properties, composition and structure of materials and analysis of radioactive isotopes. Isotope effect, dating methods, chemical separation of isotopes. Analysis of naturally occurring and artificially produced radioactive isotopes. Application of radioanalytical and nuclear spectroscopic procedures in the nuclear industry and in nuclear plant operations: radioanalysis of coolants, sipping, investigation of fuel unit inhermeticity, control of radioactive waste and emissions.

RADIATION PROTECTION

11. Radiation protection and its legislation

Biological effects of radiation. Interpretation of dose and dose rate from the standpoints of physics, metrology and biology, base and derived quantities, elements of the regulation of doses, measuring procedures of dose and dose rate. Types and methods of identification of radioactive substances leading to committed dose when incorporated inside the human body. Sources of natural and artificial radiation. Domestic and international legislation of radiation protection. Handling radiation sources. Radiation accidents. International legislation of the transportation of radioactive substances.

12. Pollution propagation and radioactive waste management

Components and sources of environmental radiation, sources of radioactive substances released into the environment. Propagation of radioactive substances in homogeneous and inhomogeneous environmental systems. Determination of the radioactivity of environmental samples by laboratory and *in situ* methods, radiation protection monitoring. Production and handling of radioactive waste, volume reduction, conditioning solutions, temporary and permanent storage of radioactive waste, investigation methods for the characterization of radioactive waste. Nuclear decommissioning.

NUCLEAR REACTOR PHYSICS

13. Nuclear physics

Properties of nuclei (nuclear radius, density, nuclear spin, quadropole and magnetic dipole moment, binding energy). Stability of nuclei, types of decay and their theoretical description, decay chains, interactions of radiation and matter. Description of nuclear models: Fermi gas model, liquid drop model, collective model. Yukawa model of nuclear forces, isospin. General properties of nuclear reactions, direct and compound nuclear reactions, resonances. Nuclear fission and fusion.

14. Reactor physics

Boltzmann transport equation and its analytical solution (Case method), diffusion approximation, basics of reactor kinetics, reactivity feedback, neutron noise methods, methods of reactivity measurement, theory of slowing down. S_n and P_l methods, finite difference and finite element discretization, process of reactor physics calculations (resonance self-shielding, cell homogenization). Reactor physics codes.

15. Thermal hydraulics

Materials used in reactors (structural materials, fuels, coolants) and their physical properties. Heat diffusion in reactor materials. Heat transfer in case of various coolants. Equations of hydraulics. Stationary description of the coolant channel in case of single- and two-phase flow. Boiling heat transfer, boiling crisis. Distribution of power and temperature in the active zone, operational limits. Thermal hydraulic system codes for nuclear reactors. Equations describing three-dimensional heat and fluid flow problems and their numerical solutions; CFD codes.

16. Monte Carlo particle transport methods

Fundamentals of Monte Carlo methods (pseudorandom numbers, sampling reactions, directions and free path lengths), their theory (solving integral equations using Monte Carlo methods, collision and path length estimators, reduction of standard deviation, adjoint Monte-Carlo) and practice (prevalent codes, typical applications).

17. Nuclear reactors and fuel cycle

Facilities of the fuel cycle (uranium mining, enrichment, fuel fabrication, spent fuel handling, reprocessing, permanent storage). Types and generations of nuclear power plants, thermal and fast reactors. Components of nuclear plants (containment system, power generation system, heat transfer circuit, safety systems, cooling, ventilation, controls). Behaviour of fuel throughout the burning cycle. Fast reactors in advanced nuclear fuel cycles (breeding, transmutation). Burnup calculations and fuel cycle simulations.

18. Operation and maintenance of nuclear reactors

Moderation and reactivity factors. Self-controlling properties of nuclear reactors. Changes in operational parameters during the campaign. Xe and Sm poisoning. Behaviour and monitoring of fuel units and the reactor vessel. Processes and detection of nuclear fuel damage. Nuclear reactor and its technological environment as a radiation source. Active zone monitoring, in-core and ex-core detectors. Instrumentation, diagnostics and operational measurements of nuclear reactors. Design of the control room.

19. Nuclear reactor safety

Domestic and international regulations of the safety of nuclear reactors. Basic safety principles for nuclear power plants. Design requirements, licensing. Design basis and its extension. Considerations and requirements for choosing the site. External and internal initial events. Deterministic and probabilistic safety assessments and their methods, tools. Risk-based or risk-informed design, principle of differentiation by safety in design. Considerations for the safe storage of spent fuel. Nuclear reactor accidents and their lessons, their effect on the progress of nuclear power.

V. RESEARCH AREAS

SOLID STATE PHYSICS
Responsible: László Szunyogh

Spin Dynamics
Magneto-Optical Spectroscopy
Unconventional Density Waves
Topological Insulators and Graphene
Non-Equilibrium Thermodynamics
Fractional Quantum Hall Effect
Ab initio Electronic Structure Calculations

NANOPHYSICS
Responsible: András Halbritter

Nanomagnetism
Investigation of Atomic Size Nanostructures
Quantumelectronics
Molecular Quantum Systems

PHYSICS OF QUANTUM SYSTEMS
Responsible: Gergely Zaránd

Quantum Field Theory
Multifractal States in Disordered Systems
Quantum Information Theory
Applications of Quantum Electrodynamics

STATISTICAL PHYSICS
Responsible: János Török

Physics of Granular Materials
Modelling of Complex Systems
Big Data Analytics
Quantum Statistical Systems

OPTICS
Responsible: Pál Koppa

Researching complex optical systems
Laser Physics
Photonics Devices
Coherent Optical Metrology

MATERIALS SCIENCE
Responsible: Gábor Kiss

Surface Physics and Surface Analysis
Development of Measuring Instruments for Materials Testing
Computational Materials Science

NUCLEAR TECHNIQUES
Responsible: Szabolcs Czifrus

Reactor Physics
Thermohydraulics and Related Researches
Nuclear Measurement Techniques and Radiochemistry
Fusion Plasma Physics and Applications

MEDICAL PHYSICS
Responsible: Dávid Légrády

Medical Imaging by Ionizing Radiations
Medical Imaging by Non-Ionizing Radiations
Radiotherapy
Radiation protection and radiation biology in medical physics

VI. SUBJECT GROUPS

Solid State Physics subject group

Modern Solid State Physics (2/2/0/v/5)
Theory of Magnetism I (2/0/0/v/3)
Theory of Magnetism II (2/0/0/v/3)
Interacting Spin Systems in Real Materials (2/0/0/3)
Many-Body Physics I (2/0/0/v/3)
Many-Body Physics II (2/0/0/v/3)
Group Theory in Solid State Research (2/0/0/v/3)
Introduction into Superconductivity Theory (2/0/0/v/3)
Localization Theory (2/0/0/v/3)
Semiconductor Physics (2/0/0/3)
Magnetic Resonance (2/0/0/v/3)
Magnetic Resonance 2 (2/0/0/v/3)
Optical Spectroscopy (2/0/0/v/3)
Electronic Structure of Solid Matter I (2/0/0/v/3)
Electronic Structure of Solid Matter II (2/0/0/v/3)

Nanophysics subject group

New Experiments in Nanophysics (2/0/0/v/3)
Physics of Mesoscopic Systems (2/0/0/v/3)
Transport in Complex Nanostructures (2/0/0/3)
The Physics of One-Dimensional Systems (2/0/0/v/3)
Nanomagnetism (2/0/0/v/3)

Physics of Quantum Systems subject group

Random Matrix Theory and Its Physical Applications (2/0/0/v/3)
Wavelets, Coherent States and Multiresolution Analysis (2/0/0/v/3)
Foundations of Density Functional Theory (2/0/0/v/3)
Variational Principles in Physics (2/0/0/v/3)
The Path Integral Method in Physics (2/0/0/v/3)
Selected Topics from Quantum Mechanics (2/0/0/v/3)
Quantum Entanglement (2/0/0/v/3)
Coherent Controll of Quantum Systems (2/0/0/v/3)
Field Theory at Finite Temperature and in Non-Equilibrium (2/0/0/v/3)
Introduction to Theoretical Plasma Physics (2/0/0/v/3)
Magnetohidrodynamics in Low Dimensional Systems (2/0/0/v/3)

Statistical Physics subject group

Scaling and Criticality (2/0/0/v/3)
Phase Transitions (2/0/0/v/3)
Non-Equilibrium Statistical Physics (2/0/0/v/3)
Statistical Field Theory (2/0/0/v/3)
Dynamical Systems (2/0/0/v/2)
Transport Processes (2/0/0/v/2)
Evolutionary Game Theory (2/0/0/v/3)
Complex Networks (2/0/0/v/3)

Optics subject group

Physical Optics (4/0/0/v/5)
Laser Physics (2/0/0/v/3)
Optoelectronic Devices (2/0/0/v/3)
Holography and Applications (2/0/0/v/3)
Optical Materials and Technologies 1 (2/0/0/v/3)
Optical Materials and Technologies 2 (2/0/0/v/3)
Optical information Processing and Data Storage (2/0/0/v/3)
Optical Metrology (2/0/0/v/3)
Fundamentals of Optical Design (2/2/0/v/4)
Quantumelectronics (3/0/0/v/4)
Basic Physics of Optical Communication
Light Sources (2/0/0/v/3)
Introduction to the Physics of Ultrafast Pulses (2/0/0/f/2)
From Femtosecond Lasers to Attophysics (2/0/0/v/2)
ELI Preparatory Laboratory (0/0/4/f/2)
Design and Construction of Laser Systems (2/0/0/f/2)
Infrared and Raman Spectroscopy (2/2/0/v/3) (2/0/2/v/3)

Materials Science subject group

Electron- and Ionoptics (2/0/0/v/3)
Electrical and Optical Properties of Solids (2/0/0/v/3)
Vacuum Physics and Technology (2/0/0/v/3)
Experimental Methods in Material Science I (3/0/2/f/5)
Experimental Methods in Material Science II (3/0/2/f/5)
Introduction to Surface Physics (2/0/0/f/2)
Surface Physics and Thin Films I (4/0/0/v/3) (2/0/0/v/3)
Surface Physics and Thin Films II (4/0/0/v/3) (2/0/0/v/3)
Fundaments and Applications of Materials Science (2/0/0/v/2)
Physical Materials Science (2/0/0/f/3)
Microtechnology and Nanotechnology (2/0/0/f/2)
Trends in Materials Science (1/0/0/v/2)
Crystalline and Amorphous Material (2/0/0/v/3)
Spectroscopy and Structure of Matter (2/0/0/v/3)

Nuclear Techniques subject group

Nuclear Non-Proliferation (2/0/0/v/2)
Low Temperature Plasma Physics (2/0/0/v/2)
Nuclear Power Plants (3/1/0/v/5)
Material Testing in Nuclear Power Plants (2/0/0/v/2)
Chemistry of Nuclear Power Plants (2/1/0/v/3)
NPP incidents' analysis (3/2/0/v/6)
Nuclear Power Plant Operation (3/1/0/v/3)
Introduction to Fusion Plasma Physics (2/0/0/v/2)
CFD Methods and Applications (2/1/0/f/3)
Chapters of High Temperature Plasma Physics (2/0/0/v/3)
Sustainable Development and Energetics (2/0/0/f/3)
Large Fusion Devices (2/0/0/v/3)
Fusion Plasma Physics Laboratory Exercises (0/0/4/f/4)
Nuclear Physics (3/0/0/v/4)
Monte Carlo Particle Transport Methods (2/0/0/v/2)
Neutron and Gamma Transport Methods (2/2/0/v/5)

Nuclear Electrodynamics (2/0/0/v/2)
Nuclear Fuel Cycle (3/0/0/v/3)
Dispersion of Radioactive Matter in Environmental and Biological Systems (2/2/0/v/4)
Safety of Radioactive Wastes (3/0/1/v/4)
Radioanalytics (3/0/2/v/5)
Calculations in Reactor Physics (3/1/0/v/4)
Control and Instrumentation of Reactors (2/1/0/v/3)
X-Ray and Gamma Spectrometry (2/0/0/v/2)
Radiation Protection 2 (2/0/2/v/4)
Simulation Techniques (2/0/1/f/4)
Collisional Transport in Magnetized Plasmas (1/2/0/f/4)
Selected Topics in Nuclear Physics (2/0/0/v/2)

Medical Physics subject group

Radiobiology (2/1/0/v/3)
Physical Basis of Radiotherapy (2/0/2/v/4)
Radiotherapy II (2/0/0/v/2)
Brachytherapy (2/0/0/v/2)
Quality Assurance and Legislation (2/0/1/v/3)
Radiation Protection in Medical Physics (3/0/1/v/4)
Magnetic Resonance and Clinical Applications (2/1/0/v/3)
Monte Carlo Methods (2/0/2/v/4)
Neutron and Gamma Transport Methods (2/2/0/v/4)
Nuclear Medicine (2/0/1/v/3)
Medical imaging (3/1/0/v/4)
Physical Basis of X-Ray Diagnostics (2/0/0/v/3)
Ultrasound Diagnostics (2/0/0/v/2)
Dosimetry in Radiation Therapy (2/0/0/v/2)