**Annex 3.**

***Form of opening (renewal) for Project /***

***Sub-project***

**APPROVED**

**JINR DIRECTOR**

**/**

**" "2023г.**

**PROJECT PROPOSAL FORM**

Opening/renewal of a research project/subproject

within the Topical plan of JINR

**1. General information on the research project of the theme/subproject**

* 1. **Theme code /** (for extended projects) -*the theme code includes the opening date, the closing date is not given, as it is determined by the completion dates of the projects in the topic.*

**2028/**

**1.2 Project/ subproject code** (for extended projects)

**1.3 Laboratory**

LHEP

**1.4 Scientific field**

FLAP- fundamental and applied research in physics with relativistic electron beams.

**1.5 Title of the project/ subproject**

“Fundamental and applied physics research with relativistic electron beams”

**1.6 Project/ subproject leader(s)**

Baldin Anton Aleksandrovich

**1.7 Project/LRIP subproject deputy leader(s) (scientific supervisor(s))**

Bleko Vitold Vladislavovich

**2 Scientific case and project organization**

**2.1 Annotation**

# It is planned to develop the research in the framework of the new collaboration FLAP (Fundamental&applied Linear Accelerator Physics collaboration): investigation of the mechanisms of electromagnetic interactions and new applications including creation of neutron sources, controllable generation of various electromagnetic radiations by relativistic electrons, development of new methods of beam diagnostics, testing and calibration of detectors for particles and radiations for collider and other acceleration experiments, applied studies in the field of radiation biology.

**2.2 Scientific case** (aim, relevance and scientific novelty, methods and approaches, techniques, expected results, risks)

**Aim of research**

Search of the new mechanisms and investigation of the fundamentals of interaction of accelerated electron beams with matter and external fields promising from the point of view of development of new science-intensive devices. Applied problems in the field of neutronography, generation of various electromagnetic radiations.

**Tasks of research**

The project includes the following main directions:

Investigation of electromagnetic response of materials under the action of bunched beam of relativistic electrons, and development of contact-free detectors for charged particle beams, electromagnetic radiators, and spintronic devices, in particular:

- study of the possibility of controlling spectral and angular characteristics of the photonic response of metamaterials excited by bunched beams of relativistic electrons, and development of controllable sources of electromagnetic radiation of the new generation with unique monochromaticity and direction;

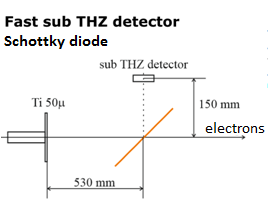


Fig. 1. Schematic diagram of experiment on registration of orientation dependence of coherent transition radiation at accelerated electron beam of LINAC - 200.

- study of polarization mechanism of electromagnetic radiation production under the action of relativistic electrons on surface structures with high local electron density, and investigation of the possibility of radiation generation in the space-charge coherence mode;

- study of the processes of interaction of relativistic electron beams with nanocapillary devices, including corrugated ones, in the mode of electron canalling formation;

- development of methods for generation, power amplification, and controlling the parameters of generated radiation; measurement of spectral-angular distribution and intensity in the THz and optical ranges for radiation generated upon interaction of electron beam with structured high electron density regions;

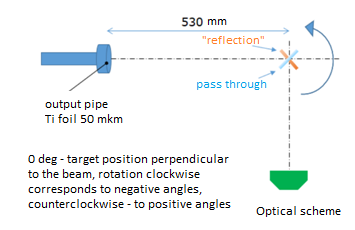


Fig. 2. Schematic diagram for registration of Vavilov-Cherenkov radiation and transition radiation from a dielectric target in the same experimental conditions.

- development of the basics of the tomographic diagnostic method for beams of relativistic charged particles in order to measure on-line beam density distribution in the transverse crosssection with high spatial resolution with minimum particle losses (see Fig. 3);

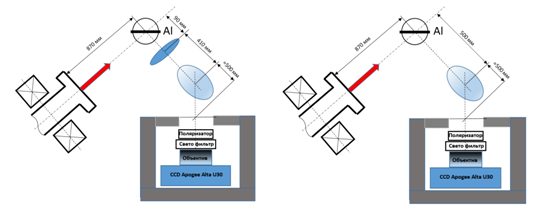


Fig. 3. One of the possible schemes for electron beam profile measurement.

- development of prototypes of devices for charged particle beam diagnostics, in particular, based on topologic insulators and Dirac semi-metals, study of these materials - development of the method for measurement of space distribution of beam density based on mathematical reconstruction of results of multi-angle scanning (see Fig. 4);

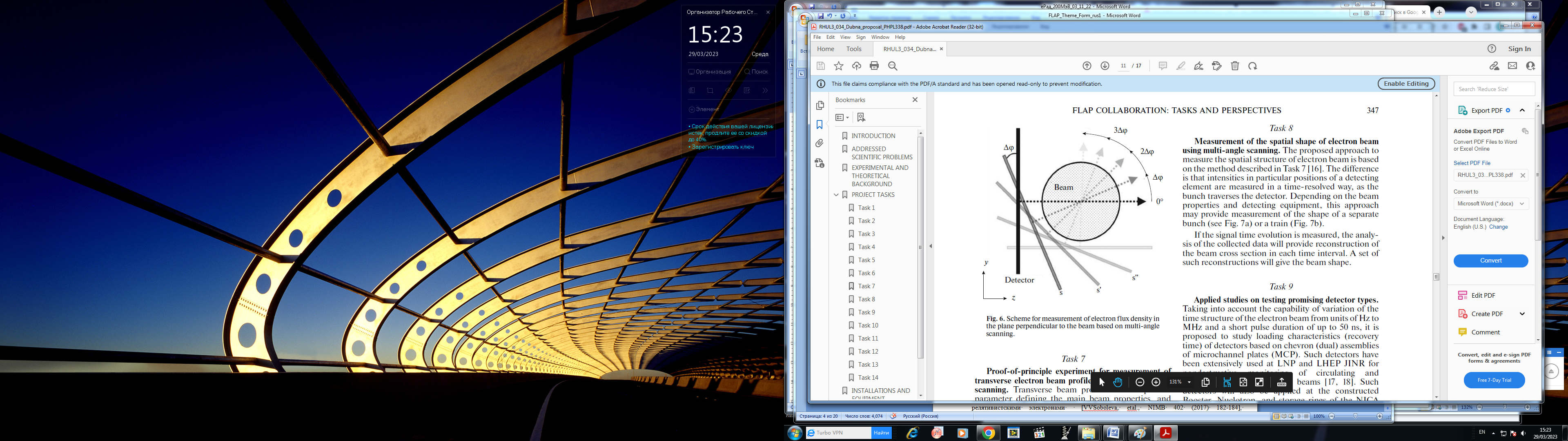


Fig. 4. Schematic diagram of electron beam density measurement using multi-angle scanning.

- study of spectral and angular characteristics and yield of neutrons generated in interaction of relativistic electron beam with matter, including ordered structures (Fig. 5);

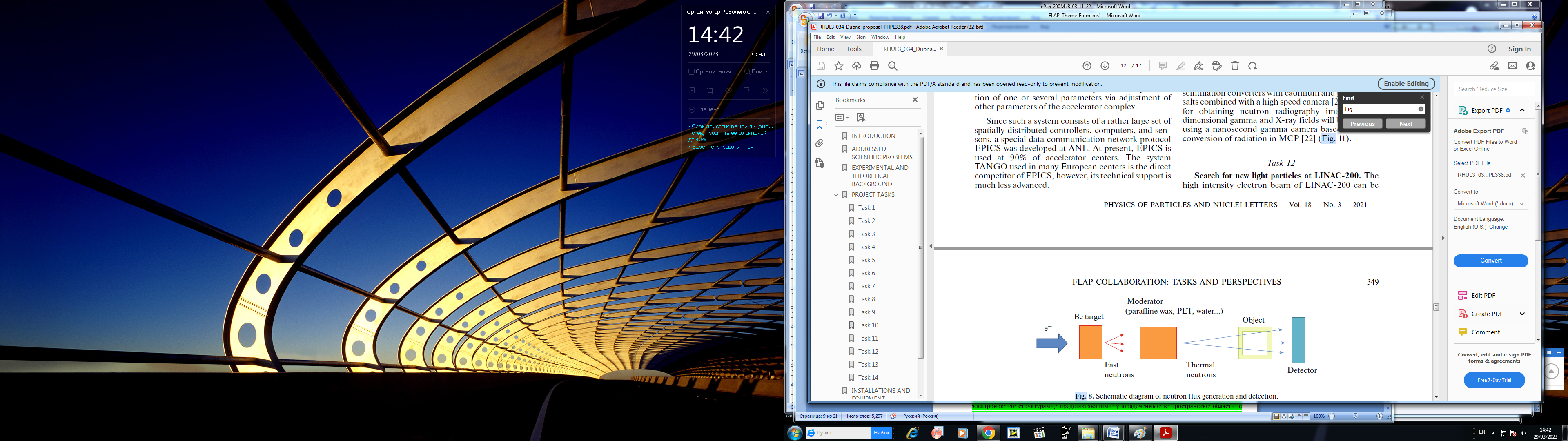


Fig. 5. Schematic diagram of neutron beam generation and detection.

- theoretical and experimental studies of the so called "dark sector" of elementary particles beyond the SM for elucidation of the origin of the "Dark matter" in the Universe, and the search of the hypothetic X17 boson which is used to explain the recently discovered ee-anomalies in spectra of excited 8Beand4Henuclei (Fig. 6);

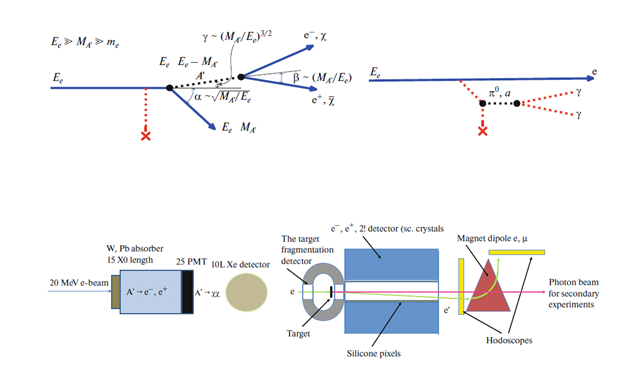


Fig. 6. Schematic diagram of the hypothetical “darkphoton” orX17 and illustration of the Primakoff effect (conversion of gamma into two gammas with axion-like particles); schematicdiagramofanexperimentalfacilityforregistrationofthehypotheticalparticle (left - zeroversion, right – more advanced design).

- scientific research of young scientists in the field of interaction of ionizing radiations with matter.

**Relevance and importance of research**

Thetopicalcharacterofthescientificpartoftheprojectisdeterminedbytheinvestigationoffundamentallynewdirectionsinthefieldofgeneration of electromagnetic radiation by relativistic electrons which is promising for development of diagnostic tools for charged particle beams, controllable sources of neutrons and electromagnetic radiation, spintronic devices, and ultrafast detectors of electromagnetic radiation of the new generation. It is important that the planned experimental studies became possible only in the recent years thanks to the creation of new functional materials (metamaterials, topological insulators, Dirac semimetals), as well as the development of new technologies (formation of arrays of oriented nanoclusters with controllable characteristics, nanoscale lithography), methods and devices for radiation registration with high spatial and spectral resolution. This allows one to anticipate fundamentally new results of the top-most level and marks the novelty and applied importance of the considered tasks.

LINAC200 is a unique installation with a number of adjustable parameters: energy which can be smoothly controlled in a range from 26 to 200 MEV; macropulse duration from 30 to 300 ns with a microbunch duration of 1 ps; beam current from 0 to 60 Ma; the possibility of tuning the pulse repetition rate within 2865 ± 20 MHz. At present, this installations with such a set of flexible and stably adjustable characteristics is unique worldwide. Moreover, LINAC - 200 has scientific and educational goals involving fundamental and applied research with participation of a large number of external users both from the Russian Federation and other countries.

There exist several installations of a similar scale in the leading international centers.

The closest with respect to its parameters scientific and educational complex CLEAR was created at CERN. The range of adjustable electron beam energy, however, is from 160 to 220 MeV for a macro pulse length from 10 to 200 ns, which is 15 times smaller than for LINAC - 200.

The CLARA facility at Daresbury (Great Britain) with a fixed energy of up to 250 MeV producing one bunch with a duration of 300 fs and a repetition rate of 10 Hz provides a possibility to study some aspects of electromagnetic radiation generation. This accelerator, however, is aimed at development of technologies for X ray free-electron lasers. Therefore, all experiments should meet the general strategy of the facility, which limits substantially the spectrum of addressed problems.

The facility LUCX at KEK (Japan) pursues scientific and educational purposes. The bunch duration in a macro pulse, however, is 10 ps, which is 10 times longer than for LINAC - 200. Moreover, for a pulse duration of 2.8 mks, the filling is just 357 MHz, which is 8 times smaller and results in generation of 1000 bunches, as compared to 104 for LINAC - 200.

Thus, LINAC - 200 may become a leading facility worldwide and be highly competitive in a number of fundamental and applied research field son interaction of relativistic electron beams and electromagnetic radiation with matter.

The studies are mainly concentrated on extensively discussed lately terahertz radiation in a spectral range from 0.1 to 10 THz, which is substantiated by the growing number of applications in this field, mainly in medicine and security systems. The field of application of electromagnetic radiation of this spectral range, including spectroscopy and nondestructive diagnostic methods, permanently broadens because the changing chemical and biological systems possess selective spectra of both absorption and reflection. THz radiation is used for investigation of the formation dynamics of nanomaterials, such as, for example, nanotubes and graphene. Low-frequency radiation is used for detection of explosives and weapons, since nonconducting materials, including clothes, concrete, and paper, are transparent for it. In this regard, generation of ultramonochromatic controllable radiation is the most preferable, in view of increasing precision and contrast in detection of details of scanned objects.

Themodernstateoftheartofdomesticandforeignresearchontheconsideredproblemisdeterminedbyfragmentary studies in some directions covered in this project. In particular, it was reported of the first observation of generation of inverse Vavilov-Cherenkov radiation by relativistic electrons [V.V.Soboleva, et al.,NIMB 402 (2017) 182-184], interacting with metamaterials, in spite of the fact that inverse refraction was predicted long ago and was observed on photon beams. Unlike this paper, the project will focus not on just observation of radiation, but on generation of radiation with the possibility to real-time control of its spectral and angular distribution via changing dielectric properties of targets. The solution of this task is of fundamental importance for future development of efficient sources of terahertz radiation which are already in great demand.

Until now, the study of the processes of passage of accelerated charged particles through matter was performed mainly for heavy positive particles (protons and ions), and low energy electrons (to 10 keV). The existing models of electron interaction with surfaces are just descriptive. Thus, the novelty of the formulated problems is the investigation of these processes for electrons with energies of order of 10-100 MeV in the conditions of self-organized canalling, and electron passage through nano- and micro-capillaries, including oriented arrays, which is interesting from the point of view of elucidation of the feasibility to form relativistic electron beams with a micron and submicron spatial scale.

Generation of radiation by a beam of relativistic electrons interacting with high electron density regions, Dirac semimetals, and topological insulators, is a fundamentally new direction opening prospects for development of novel approaches to controllable generation of electromagnetic radiation in a wide spectral range.

Substantiation of the feasibility of achieving formulated tasks and obtaining expected results.

All planned research is based on the unique experience of the collaboration team in the field of interaction of relativistic charged particles with matter and external electromagnetic fields. The fundamental basis of all formulated tasks are the well known principles of electrodynamics and physics of the condensed state. Some planned experiments are based on the calculations and simulations performed earlier by the team members, which allowed one to estimate the feasibility of experimental detection of the sought effects. The possibility of measurement of the studied quantities in the planned experiments is substantiated by the unique experience of the team at different accelerators (LINAC200 at JINR, Dubna; CLEAR at CERN; PETRA at DESY; CLARA at Daresbury; «Pakhra» at LPI) and the methods and techniques of measurement in the spectral range of radiation from several GHz to gamma radiation.

**Basic scientific methods and approaches**

Spectralandangularcharacteristicsofradiationinarangeof1 GHz - 10 THz will be measured by high sensitivity detectors: Schottky diodes, pyroelectric sensors, and bolometers. High spectral resolution (~10-7) in a range up to 50 GHz will be achieved by the spectrum analyzer with a pyramidal antenna, and in a range up to 600 GHz by the heterodyne system.

Spectral and angular characteristics of radiation will be measured by PEM – based detectors (measurements in the atmosphere) and SEM – and MCP – based detectors (in vacuum); sensitive CCD or CMOS cameras with high spatial resolution will be main lyused in the optical range; in the range from vacuum UV (110 nm) to Xrays (1-100 keV) measurements will be performed based on modern spectrometers, such as sliding incidence spectrometer McPherson 248/310 Gin combination with Hamamatsu R5150-10 electron multiplier, which allows one to measure spectra with an energy resolution of at least 0.1%; vacuum-compatible semiconductor spectrometers Amptek with thin X123SDDFASTC1 and X123SDDFASTC2 windows, which provide measurements in the required spectral range with a counting rate of up to 106 photons per second and an energy resolution of about 100 eV.

The gamma spectrum in an energy range of 0.1-6 MeV will be measured by the scintillation spectrometer SDMF1206 with the function of discrimination of neutron contribution based on the analysis of the pulse shape, which will ensure simultaneous monitoring of the neutron background.

Background suppression in measurements will be performed as follows:

- shielding of the measurement equipment and application of a separate ground connection for it;

- strong collimation of the observed signal, which will cut off the background of particles emitted by elements of the facility;

- synchronization of data acquisition with the electron beam time structure, which will cut off the background detected during the idle time without a useful signal;

- installation of magnetic deflectors for the charged component of the background.

All above methods were developed, tried out, and are successfully used by the collaboration team at different installations, including those where experiments of a similar character are addressed.

Positioning of targets and detectors in vacuum.

Most of the experiments imply measurements in vacuum, which poses the problem of controlling the positions of detectors and targets, as well as other elements of the experimental facility, remotely in the vacuum volume. These specific requirements will be met by using vacuum motorized platforms with step motors. The collaboration team possesses a vast experience in successful development, manufacture, and maintenance of such elements.

All experiments will be performed based on preliminary analytical calculations and mathematical simulation of expected radiation characteristics, in order to determine the optimal experimental conditions. Analytical calculations will be performed based on the classical approaches to solution of such problems, first of all, via analysis of the Maxwell equations with account of boundary conditions defined by the geometry of the considered processes of interaction of relativistic electrons with targets. Solutions from the theory of polarization bremsstrahlung radiation of relativistic charged particles will be applied for examination of polarization mechanisms of radiation generation. Mathematical simulation will be performed based on the widely used software GEANT and CST-Studio.

Most of the formulated tasks are not only novel in their formulation, but open new directions for further studies in the field of the physics of radiation produced by accelerated charged particles.

**Expected results**

The main results of the project will be:

- a unique scientific research facility for investigation of the mechanisms of generation of electromagnetic radiation in a wavelength range from 1 mm (microwave range) to 1 pm (gamma radiation) produced in interaction of relativistic electron beams with matter and external electromagnetic fields will be created;

- fundamentally new approaches to generation of electromagnetic radiation with controllable characteristics based on targets produced from functional materials will be developed;

- new nondestructive methods for diagnostics of charged particle beams will be developed and tested;

- prototypes of detectors of charged particles and radiations for experiments at SPD and MPD NICA will be developed, tested, and calibrated;

- a pulsed neutron source with a time-of-flight system for measurement of the neutron energy spectrum in a range from 10 keV to 18 MeV will be developed and created. The test bench for investigation of neutron spectra from various targets from Al to Pb, as well as for calibration of neutron detectors, will be created;

- experimental studies on substantiation of the possibility of the search of particles beyond the SM and states of nuclear matter in a mass range of the hypothetical X17 will be performed. Prototypes of detectors for experiments in this mass range with account of the parameters of LINAC - 200 and background conditions in the experimental hall will be manufactured and tested;

The main risk to fail achieving the formulated tasks of the project is financing below the estimated cost, including under financing of the necessary work to provide stable operation of LINAC - 200 with the announced parameters.

**2.3 Estimated completion date**

5 years

**2.4 Participating JINR laboratories**

LHEP

LNP

LRB

LIT

**2.4.1MICC resource requirements**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Computingresources** | **Distribution by year** | | | | |
| 1styear | 2nd year | 3rdyear | 4th year | 5th year |
| Data storage (TB)  - EOS  - Tapes |  |  |  |  |  |
| Tier 1 (CPU corehours) |  |  |  |  |  |
| Tier 2 (CPU corehours) |  |  |  |  |  |
| SC Govorun (CPU core hours)  - CPU  - GPU |  |  |  |  |  |
| Clouds (CPU cores) |  |  |  |  |  |

**2.5. Participating countries, scientific and educational organizations**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Organization** | **Country** | **City** | **Participants** | **Type**  **of agreement** |
| 1.Belgorod National Research University | Russia | Belgorod | A. Kubankin  R. Nazhmudinov  I. Kishchin  V. Zakhvalinskii  L. Myshelovka  K. Vokhmyanina | MoU |
| 2.National Research Tomsk Polytechnic University | Russia | Tomsk | S. Stuchebrov  A. Potylitsyn  A. Bulavskaya  Yu.Cherepennikov  M.V.Shevelev  Vukolov A.V.  Shkitov D.A.  Toktaganova M.M.  Jurnich Blazo (Serbia) | MoU |
| 3.Petersburg Nuclear Physics Institute, National Research Center "Kurchatov Institute"  4.St. Petersburg Polytechnic University | Russia | St. Petersburg | V. Kim  E. Kuznetsova  A. Zelenov | Protocol |
| 5.VTC OOO “Baspik” | North Ossetia-Alania | Vladikavkaz |  | An agreement |
| 6.IPTP | Russia | Dubna | Smirnov A.A.,  Gazizov I.M. | Protocol |
| 7.Marafon | Russia | Moscow | Chepurnov A.S. | Protocol |
| 8.INP BSU | Belarus | Minsk | S.A.Maksimenko,  K.Batrakov | MoU |
| 9.John Adams Institute at Royal Holloway, University of London | UK | Egham, Surrey | P.Karataev  K. Fedorov |  |
| **10.Federal State Unitary Enterprise Russian Federal Nuclear Center - All-Russian Research Institute of Experimental Physics** | **Russia** | **Sarov** | Yu.Bazarov  M. Karpov | Protocol |
| 11.Center for Theoretical and Experimental Particle Physics (СTEPP)  Of UNAB (Universidad Andres Bello) | Chile | Santiago | S. Kuleshov  J. Zamora Saa |  |
| 12.KEK: High Energy Accelerator Research Organization  SOKENDAI: The Graduate University for Advanced Studies | Japan | Tsukuba | A.Aryshev  K.Popov |  |
| 13.Institute of Applied Problems of Physics, National Academy of Sciences of Armenia | Armenia | Yerevan | V. Kocharyan  A. Mkrtchyan  A. Movsisyan  L. Grigoryan  A. Saharian | MoU |
| 14.Department of Molecular Physics, Faculty of Physics, Yerevan State University | Armenia | Yerevan | L. Aloyan  Y. Dalyan  N. Karapetyan  A. Avetisyan  A. Shahbazyan | MoU |

**2.6. Key partners** *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program. An example is JINR's participation in the LHC experiments at CERN).*

**3. Manpower**

**3.1. Manpower needs in the first year of implementation**

|  |  |  |  |
| --- | --- | --- | --- |
| **№№**  **n/a** | **Category of personnel** | **JINR staff,**  **amount of FTE** | **JINR Associated**  **Personnel,**  **amount of FTE** |
| 1. | research scientists | A.Baldin  E. Baldina  V. Kobets  D. Bogoslovsky  V. Bleko  V.Bleko  A.V.Butenko  V.V.Glagolev  A. Zhemchugov  E.Klevtsova  A.P.Sumbaev  M. Gostkin,  A. Fedorov,  E.Bushmina  14 | I. Samofalova,  A. Trifonov,  K. Yunenko  A. Dorokhov  4 |
| 2. | engineers | A. Beloborodov  P. Kharyuzov  D.Korovkin  A.Safonov  Nozdrin M.  Skrypnik A.V.  Shabratov V  Demin D.L.  Troyan Y.A.  Kuharev V.A.  10 |  |
| 3. | specialists |  |  |
| 4. | office workers |  |  |
| 5. | technicians |  |  |
|  | **Total:** | **24** | **4** |

**3.2. Available manpower**

**3.2.1. JINR staff**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **No.** | **Category of personnel** | **Full name** | **Division** | **Position** | **Amount**  **of FTE** |
| 1. | research scientists | A.Baldin  E. Baldina  V. Kobets  D. Bogoslovsky  V. Bleko  V.Bleko  A.V.Butenko  E.Klevtsova  A.P.Sumbaev  E.Bushmina  V.V.Glagolev  A. Zhemchugov  M. Gostkin, | LHEP  LNP | Head of dep.  SSR  Head of sector  SR  Head of sector  SSR  LHEP Director  Dep.of head of dep.  Leading scientific researcher  Dep.director LNP  Deputy head of department  Head of sector | 0.7  0.7  0.7  0.8  0.9  0.8  0.2  0.7  0.5  1.0  0.2  0.3  0.3 |
| 2. | engineers | Beloborodov A.  Kharyuzov P.  Korovkin D.  Safonov A.  Troyan Y.A.  Nozdrin M. V.A.Kuharev  Skrypnik A.V.  Shabratov V  Demin D.L.  Fedorov A. | LHEP  LNP | Engineer  Head of group  Engineer  Engineer  Engineer  Head of group  senior engineer  Engineer  Engineer  Chief Engineer of  installation  Lead Engineer | 0.3  0.5  0.7  0.7  0.6  0.7  0.5  0.8  0.7  0.6 |
| 3. | specialists |  |  |  | 7.1 |
| 4. | technicians |  |  |  | 8.0 |
|  | **Total:** | **24** |  |  | **15.1** |

**3.2.2. JINR associated personnel**

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Category of personnel** | **Partner organization** | **Amount of FTE** |
| 1. | research scientists |  |  |
| 2. | engineers |  |  |
| 3. | specialists |  |  |
| 4. | technicians |  |  |
|  | **Total:** |  |  |

**4. Financing**

**4.1 Total estimated cost of the project/LRIP subproject**

The total cost estimate of the project (for the whole period, excluding salary).

The details are given in a separate table below.

**4.2 Extra funding sources**

Expected funding from partners/customers – a total estimate.

**Project (****LRIP subproject) Leader** \_\_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_/

Date of submission of the project (LRIP subproject) to the Chief Scientific Secretary: \_\_\_\_\_\_\_\_\_

Date of decision of the laboratory's STC: \_\_\_\_\_\_\_\_\_ document number: \_\_\_\_\_\_\_\_\_

Year of the project (LRIP subproject) start: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

(for extended projects) – Project start year: \_\_\_\_\_\_\_

**Proposed schedule and resource request for the Project / LRIP subproject**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Expenditures, resources,**  **funding sources** | | | **Cost (thousands**  **of US dollars)/**  **Resource requirements** | **Cost/Resources,**  **distribution by years** | | | | |
| 1st year | 2nd year | 3rd year | 4th year | 5th year |
|  | | International cooperation |  | 25 | 25 | 25 | 25 | 25 |
| Materials |  | 40 | 40 | 40 | 40 | 40 |
| Equipment, Third-party company services |  | 35 | 35 | 35 | 40 | 40 |
| Commissioning |  | 10 | 10 |  |  |  |
| R&D contracts with other research organizations |  | 5 | 5 | 5 | 10 | 10 |
| Software purchasing |  | 10 | 10 | 10 |  |  |
| Design/construction |  |  |  |  |  |  |
| Service costs (*planned in case of direct project affiliation)* |  |  |  |  |  |  |
| **Resources required** | **Standard hours** | Resources |  |  |  |  |  |  |
| * the amount of FTE, |  | 10 | 10 | 10 | 10 | 10 |
| * accelerator/installation, |  | 1000 | 1000 | 1000 | 1000 | 1000 |
| * reactor,… |  |  |  |  |  |  |
| **Sources of funding** | **JINR Budget** | JINR budget *(budget items)* |  |  |  |  |  |  |
| **Extra fudning (supplementary estimates)** | Contributions by  partners  Funds under contracts with customers  Other sources of funding |  |  |  |  |  |  |