MINISTRY OF EDUCATION, YOUTH AND SPORTS

# Final Report on the Realization of the Large Research Infrastructure (LRI) 2016-2019

# CERN-CZ

Full name of the LRI: Research infrastructure for experiments at CERN

LRI's code: LM2015058

Recipient: Institute of Physics of the CAS

Another participant/s of the LRI:

Charles University

Czech Technical University in Prague

Nuclear Physics Institute of the CAS

Palacký University Olomouc

Technical University of Liberec

University of West Bohemia

Principal investigator of the LRI: doc. Mgr. Alexander Kupčo, Ph.D.

Website address of the LRI: http://www.particle.cz/infrastructures/cern-cz/index.html

## PART I. - DESCRIPTION

### A. Mission of the LRI, Basic Overview

I. Describe the mission and objectives of the LRI, scope of services the LRI provides to the scientific community, focus of the LRI´s activities, capacities dedicated by a host institute and the project partners, state of development at the beginning and at the end of the funding period.

The LRI CERN-CZ organizes and supports the participation of universities and research institutions from the Czech Republic (CR) in the international laboratory CERN (European Organization for Nuclear Research) in Geneva. With the world's largest proton and heavy ion accelerator, the Large Hadron Collider (LHC), CERN plays a worldwide leading role in research of elementary particle physics and behavior of matter at extremely high energies. The goal of research at CERN is to broaden our knowledge of the basic laws governing matter behavior, including the principles under which our universe evolves.

The international organization CERN was founded in 1954 by twelve European countries. Today, CERN has a total of 23 member countries that take care of the operation of the laboratory. The Czech Republic has been a member of CERN since 1992 (at that time still as the Czech and Slovak Federal Republic). The CERN Council authorized the extension of the mandate beyond Europe and in December 2013 Israel became the first non-European member state of the organization. From the very beginning, CERN has been a shining example of international cooperation and excellence in particle physics for 65 years.

CERN focuses on fundamental research of the properties of matter at extreme energies. The primary users are therefore from an academic scientific community, i.e. scientists from universities and laboratories around the world, with a large, roughly one-third share of students. According to the latest data from 2018, a total of 12,569 experts from all over the world participated in CERN research, of which 7,385 users were from CERN member countries. Among them 258 (3.5% of member countries) were users from Czech (CZ) research institutions.

CERN operates and hosts a number of unique accelerators and experiments. The best known and most important one is the LHC, fully operational since late 2009, fifteen years after project approval. The most significant result so far is the discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments. During its operation, the LHC delivered several tens of inverse femtobarns ($fb^{-1}$) of proton-proton collisions at center-of-mass energy of 7 and 8 TeV and 150 $fb^{-1}$ at 13 TeV, which is the highest proton-proton collision energy achieved in the Earth laboratory. Higher LHC collision energy and higher luminosity allow more detailed research of the Higgs boson properties and expand the LHC discovery potential for searches for new particles and new phenomena in particle physics and ultra-relativistic nuclear physics. This was the main scientific programme of the LHC experiments in the years 2016-2019, and this defined as well the main scientific goals of the LRI CERN-CZ in the reported period.

The LHC High Luminosity Upgrade (HL-LHC) is planned for the next long LHC shutdown currently scheduled for 2025-2027. In connection with HL-LHC, it is also necessary to upgrade the LHC experiments in order to be able to operate them in new harsh conditions of more intense proton beams. Besides the participation in the operation of the experiments, the preparation for the HL-LHC upgrade of the ATLAS and ALICE experiments was the main activity of CERN-CZ in 2016-2019.

The aim of CERN-CZ is to support the development, construction, maintenance and operation of scientific facilities in CERN experiments with Czech participation. This includes the local infrastructure and laboratories in the CR, which are necessary for the research, development and production of these detectors, and computing tools for large scale data processing. The LRI is developing new technologies for particle detectors including their applications, especially in the field of calorimetry and semiconductor tracking detectors. The LRI's technical scope covers such areas as:

- design and construction of detectors,
- development of radiation-hard semiconductor detectors and electronics,
- cooling,
- cryogenics,
- vacuum technology,
- electronic and mechanical design,
- large scale data processing.

The portfolio of services includes: operation and maintenance of detectors, in particular those that have been built partially in the CR; upgrade and construction of new detectors; research and development of new technologies and detectors for future upgrades and new projects; operation of a computer center serving as a national Tier2 center in the hierarchy of CERN computer network; coordination of projects at CERN with CZ participation in cooperation with the *Committee for Collaboration of the CR with CERN*; representation and exercise of our country's rights in the governing and advisory bodies of CERN and individual experiments.

Unique scientific experimental facilities, which were constructed with a contribution from the CZ institutions, form the core of the LRI. Continuous participation in their operation, maintenance and upgrades is a necessary condition enabling CZ scientists to have access to the unique data collected by these devices. This is the core benefit of CERN-CZ for the Czech user community. Scientists from CZ research institutions can thus contribute adequately to the excellent world-class results in the field of particle and nuclear physics produced by the experiments at CERN.

The following seven research institutions are involved in the activities of CERN-CZ:

- Institute of Physics of the CAS (FZU), host institution,
- Charles University (CU)
- Czech Technical University in Prague (CTU),
- Nuclear Physics Institute of the CAS (NPI),
- Palacký University Olomouc (UPOL),
- Technical University of Liberec (TUL),
- University of West Bohemia in Pilsen (UWB).

Within the LRI, CZ research institutions contribute to the following experiments and projects at CERN:

- LHC experiments: ATLAS, ALICE, TOTEM, MoEDAL,
- other non LHC experiments: COMPASS, NA62, AEGIS, OSQAR, nTOF, WITCH,
- research and development (RD) projects: MEDIPIX / TIMEPIX, AIDA, RD50, RD53, RD18, CALICE, FCC.

The LRI institutions were involved in the design, construction, testing and commissioning of the key components of the ATLAS (https://atlas.cern/) and ALICE (http://aliceinfo.cern.ch/) experiments. For the ATLAS experiment, these were: parts of the Inner Detector based on strip and pixel semiconductor sensors, TileCal hadron calorimeter, forward proton detectors ALFA and AFP, ATLAS-MPX radiation background detectors, and muon detector radiation shielding. In the case of ALICE experiment, it was mainly electromagnetic calorimeter PHOS. There were also a few other contributions to smaller experiments, like vacuum parts of Roman Pots for TOTEM. Experts from CERN-CZ have contributed to solving a number of problems in the construction of detectors, such as cooling semiconductor detectors, electronics, radiation shielding and others, and are intensively involved in the upgrade of these detectors for HL-LHC. They are also involved in the operation and maintenance of these detectors during data taking campaigns. LRI's teams contributed similarly to other experiments at CERN with the participation of CZ institutes.

Below we describe the advanced infrastructure used during the construction and operation of the detectors by highly qualified LRI teams of experts.

For testing, development and production of semiconductor detectors:

- clean laboratories at FZU, CU, CTU, and NPI,
- equipment for very accurate quality testing of semiconductor sensors,
- automatic and manual probe stations,
- metrology stations,
- various test devices based on laser, X-ray, and radioactive emitters, and accelerator testing methodology,
- electronic and mechanical workshops,
- optical laboratories at UPOL.

This infrastructure is currently being used to fulfill CERN-CZ's commitments to HL-LHC upgrades of ATLAS and ALICE experiments. The most significant achievement in 2016-2019 is the construction of joint clean laboratory for testing strip semiconductor detectors and modules assembly for new ATLAS Inner Tracker detector (ITk). The laboratory was built from the funds of the LRI CERN-CZ with a significant contribution from the hosting and participating institutions, which took care of the laboratory equipment in the extent of approx. 20 million CZK (Czech Crown), see the detailed list in section I-C-I and II-C-I. The hosting institution also provided clean rooms.

The following tools are used to model the properties, design and construction of detectors: the GEANT4 program for simulating the passage of particles through the material; the SILVACO program for modeling the production of semiconductor sensors; specialized programs for detectors ATLAS and ALICE and tools for design and modeling microelectronic circuits CADENCE and TCAD.

The LRI has also a modern laboratory at CU for the development and testing of gas detectors. Low temperature millikelvin technologies at CU are used to design and develop cryogenic polarized targets for the COMPASS experiment.

Optical laboratories in Joint Laboratory of Optics in Olomouc, operated jointly by FZU and UPOL, were used for the design and construction of optical parts of timing detector for ATLAS forward proton detector AFP.

A dedicated computing facility was established at FZU more than 10 years ago. It serves as a center for the large-scale data processing for experiments in particle physics. The center was expanded to include external workplace at NPI dedicated mainly to storage services. The resources of the center, about 6,400 CPUs with the capacity of 66,000 HS06 units, and 4 PB disk space, are also used for neutrino experiments in Fermilab and astro particle experiments. For LHC experiments, this computing center ensures the operation of the so-called Tier2 center in the hierarchy of CERN computing centers and also provides capacity for the LRI's users for local data processing.

The main objective of the LRI is to meet the commitments of the LRI's member institutions to the CERN experiments, whether of financial, operational or maintenance nature, or the commitments towards the construction of new detectors. Individual LHC experiments present their status and achievements twice a year to the LHC Resource Review Board (LHC RRB), a board for LHC experiments which is comprised of delegates of various national funding bodies involved in financing the experiments. The reports include an overview of contributions for each National Agency. The Ministry of Education, Youth and Sports (MEYS) has its delegate in the LHC RRB as well. This delegate controls the LRI's achievements and fulfilment of the obligations of the CZ institutions towards the LHC experiments. We can state that all our institutional commitments have been fulfilled during the duration of the project in 2016-2019. Other outputs of the LRI are publications of technical character that were created during the development and operation of the LRI. These are regularly reported in the annual LRI's reports, together with the scientific results obtained by users of the facilities operated with the contribution from the LRI CERN-CZ, see sections II-A-I and II-A-II.

## B. Management Structure and Research Team

I. Describe the management structure and organizational chart of the LRI, its changes during the funded period and its anchorage within the host institution(s).

The organization of the LRI's management is based on the past successful experience of CZ research teams in the construction and operation of detectors at CERN, and on experience from the organization of research in the LRI's institutions. The specificity of CERN-CZ is the large number of participating institutions in the project, as this infrastructure organizes and ensures the participation of practically all Czech institutions involved in experiments at CERN.

The hosting institution of LRI is the Institute of Physics of the Czech Academy of Sciences (FZU). Elementary particle physics is one of the priority areas of research at FZU. This is also reflected in the organizational structure of the institute, the Division of Elementary Particle Physics is one of the six institute's research divisions. It consists of four departments: Department of Experimental Particle Physics, Department of Detector Development and Data Processing, Department of Particle Theory and Cosmology, and Department of Astroparticle Physics.

For a long time, FZU has been playing a leading role in the organization of the CZ particle physics community and its participation at CERN. Throughout the whole period of CERN membership of the CR, it was the main recipient of grants for cooperation between Czech research institutes and CERN. The relevant advisory body of the Ministry of Education, Youth and Sports (MEYS), the Committee for Cooperation of the Czech Republic with CERN (VS CERN) is also working on the

premises of the institute. FZU supports research at CERN by providing laboratories used for development and construction of experimental devices for the CERN experiments. It also operates a computing center dedicated primarily to large scale data processing in particle physics, which is used also for astro-particle physics experiments and solid state physics. Over the past decade, FZU has invested more than 50 million CZK into the construction, equipment and operation of laboratories and spends approximately 8 million CZK a year on the operation of the computing center.

The LRI's management is based on two pillars: on participation in the management of the CERN laboratory and in the management of individual experiments, and on the LRI's own management structure.

CERN's main governing body is the CERN Council. Each member state has one vote in the Council and has the right to send to the CERN Council a maximum of two delegates. Delegates may be accompanied at Council meetings by other advisers. As a rule, there is one delegate from the country's political representation and one scientific delegate. In the case of the CR, the delegates to the CERN Council are the Ambassador of the Czech Republic's Permanent Mission in Geneva and the scientific delegate appointed by the MEYS. The scientific delegate is a member of the Committee for Cooperation of the CR with CERN, currently he is the chairman of this advisory body of MEYS. The CERN Council elects the President of the Council and two Vice-Presidents. The Council appoints the Director-General of CERN for a five-year term and approves his / her top management team. The Director informs the Council of the status of the laboratory, submits to the Council the draft budget and the medium-term development plan of the organization and submits proposals for the extension of CERN by new associated or full members. The CERN Council has several subordinate bodies, an advisory body ECFA (European Committee for Future Accelerators - the CR is represented by three delegates) and external auditors (usually the Supreme Audit Office of a CERN member state), currently from Finland (National Audit Office of Finland).

The subordinate bodies of the CERN Council are: the CERN Finance Committee, the Scientific Policy Committee, Tripartite Employment Conditions Forum (TREF), the Standing Advisory Committee on Audits, and the PFGB (Pension Fund Governing Board). In the Finance Committee, the Czech Republic has two delegates, one of whom is also a delegate in TREF.

The activities of large LHC experiments are presented at the LHC RRB meetings. The CR is represented in LHC RRB by delegate of MEYS and leading scientists of Czech experimental groups. In the case of the CR, it concerns three experiments ATLAS, ALICE, and TOTEM, plus large scale data processing on the LHC Grid. LHC RRB approves yearly operational budgets of experiments and new projects, like HL upgrades of LHC experiments. Approved commitments are then part of corresponding Memoranda of Understanding (MoU).

Participation in CERN Council meetings, subordinate and advisory bodies and the operation of the CERN VS Secretariat is supported from the LRI's budget. The same applies for the representation of the CZ institution in management and governing bodies of individual CERN experiments and projects.

The main governing body of LRI CERN-CZ is the Executive Board chaired by the LRI's responsible scientist. The Executive Board currently has 14 members:

- Alexander Kupčo (FZU), chairman,

- Guillermo Contreras (CTU),
- Tomáš Davídek (CU), principal investigator of project LTT17018,
- Zdeněk Doležal (CU),
- Vyacheslav Georgiev (UWB),
- Jiří Chudoba (FZU), principal investigator of related OPVVV project,
- Filip Křížek (NPI),
- Jiří Kvita (UPOL),
- Rupert Leitner (CU), chairman of VS CERN, delegate of the CR in the CERN Council
- Vojtěch Petráček (CTU),
- Karel Smolek (CTU),
- Miroslav Šulc (TUL),
- Michal Šumbera (NPI),
- Václav Vrba (CTU).

The Board includes representatives of all LRI participating institutions, representatives of the main working groups, principal investigators of the associated project in the Operational programme Research, Development and Education (OP VVV), principal investigator of project LTT17018 *"Getting new knowledge of the microworld using the CERN infrastructure"*, and chairman of the VS CERN, who is at present also scientific delegate of the CR in the CERN Council. The Board meets as necessary, at least four times a year. It deals with LRI's operational issues, prepares and controls the fulfilment of the annual financial plans, oversees the fulfillment of the Czech institutions' obligations towards experiments at CERN, and prepares documents for interim and final reports. It also supervises the implementation of the associated OP VVV project.

II. Describe the composition and functioning of supervisory and advisory bodies (if established):

The LRI and its Executive Board is supervised by VS CERN. The Committee is an advisory body to the MEYS and has more than twenty years of experience with all aspects of membership of the CR at CERN. VS CERN is hosted by FZU, which is also the hosting institution of the LRI. VS CERN consists of representatives of the relevant ministries, institutes of the Academy of Sciences of the Czech Republic and Czech universities cooperating on CERN projects, as well as representatives of the CR in the management and advisory bodies of CERN, and also the leading scientists of Czech teams from CERN experiments with the largest Czech participation.

VS CERN meets regularly at least four times a year before meetings of CERN's top bodies and financial bodies of the main experiments. At VS CERN meetings, the positions of our delegations at CERN Council meetings and other bodies are discussed. At these meetings, the chairman of the LRI's Executive Board also reports on the activities of the LRI. VS CERN comments the activities and approves important proposals submitted by the LRI's chairman, e.g. the composition of the LRI's Advisory Council, etc. The chairman of the VS CERN is also a member of the Executive Board of the LRI CERN-CZ.

The role of the advisory body to the LRI is fulfilled by the Advisory Board of CERN-CZ. The Board consists of renowned external experts who have been selected in such a way that their professional qualifications correspond to the main research objectives of the LRI. It has currently five members:

- Josef Žáček (CU, Prague), chairman,

- Federico Antinori (University and INFN, Padua),
- Stanislav Tokár (Comenius University in Bratislava),
- Wolfgang Lohmann (Deutsches Elektronen-Synchrotron DESY, Hamburg),
- Frank Simon (Max-Planck-Institut fur Physik, Munich).

The Advisory Board meets once a year in December on the premises of the hosting institution. The first part is an open session together with the LRI's Executive Board. Members of VS CERN are invited as well. In this meeting, the main activities of the LRI in the past year and the LRI's budget are presented, and plans for the coming years are discussed. In the second, closed part, the Advisory Board formulates its opinions and recommendations. These are then submitted to the LRI's Executive Board and VS CERN in the form of minutes. The Advisory Board assesses the level of professional and operational activities of the infrastructure, expresses its opinion and makes recommendations on newly planned activities and on the long-term strategic plan. It also comments on the budget spending and assesses the effectiveness of the use of financial resources. The minutes of the last three Advisory Board meetings are attached to the report.

III. Describe generally (not by names) human resources background over the entire funding period – classification of employed and hired persons, including full-time equivalent (FTE). Fill in the table (if needed convert amount of hours to FTEs):

| **Number of FTEs** | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|
| Senior scientists | 11,31 | 11,26 | 8,23 | 8,68 |
| Junior scientists | 3,67 | 3,29 | 3,37 | 4,69 |
| PhD students | 3,16 | 3,88 | 2,13 | 1,95 |
| Students | 0,96 | 0,93 | 1,45 | 1,45 |
| Technical staff | 4,79 | 4,29 | 5,34 | 4,68 |
| Administratives | 1,1 | 1,19 | 1,43 | 1,47 |
| Other | 0,07 | 0 | 0 | 0 |
| **Total** | 25,04 | 24,83 | 21,94 | 22,92 |

The operation of the LRI CERN-CZ requires about 50 FTE (Full Time Equivalent). Of these, only a part of approx. 10 FTE was covered from the LRI resources in the form of the main labour contract (HPP), side labour contract (DPP), and work arrangement (DPC). The rest of the personnel costs was carried by the CERN-CZ institutions. The necessary work capacities were ensured in the work description documents of the relevant employees. Details are available in Part III-A-II.

The table above shows human resources whose activity was paid at least partially from the resources of the LRI, i.e. in addition to workers with HPP, DPP and DPC, these are the workers who received personal bonuses from the LRI budget. Workers who did not draw personnel costs from the LRI budget are not recorded in the table.

The contribution of senior scientists with Ph.D. to the LRI operation was in 2018 about 38%, junior researchers with Ph.D. represented 15%, Ph.D. students 10%, technicians and engineers including IT staff 24%, and administrative and other positions 6%. The composition of the team was stable over time and similar numbers are valid for other years of project.

In the context of Memoranda of Understanding on the operation and maintenance, larger experiments, such as ATLAS and ALICE, keep records of human resources provided by individual institutions. The ATLAS experiment records shifts served in the control room, shifts served by experts responsible for individual parts of the apparatus (so called on-call experts), and keeps track of other operational tasks. It also records the institution's contribution to the HL-LHC upgrade of the ATLAS experiment. In 2018, the experiment ATLAS recognized 24.4 FTE for Czech institutions participating in ATLAS, see part I-D-II for details. The ALICE experiment only records shifts in the control room. Here, the CZ institutions served 130 shifts in 2018, i.e. about 0.5 FTE. The LRI contribution recognized by the two CERN experiments is around 25 FTE. The scope of CERN-CZ activities is, of course, larger. Except for not-recorded activities on CERN experiments (technical work and upgrades for ALICE, other smaller experiments, etc.), this includes work on research and development projects at CERN, management and representation of the CR and Czech institutions in CERN experiments and projects, and work in local laboratories and computer center, as well as an administration of the LRI.

## C. Structure of Users and Utilization

I. Describe capacities and instrumentation dedicated to LRI by institutes involved, principles of granting access to the LRI, indicate number of accesses from the Czech Republic and from abroad and volume of utilization of LRI (e.g. data produced, time allocated, services provided).

Research institutions from the LRI CERN-CZ participate in international experiments at CERN. This defines the range and structure of users. User access to data is governed by the rules of individual experiment and general CERN rules. The approach is organized on an institutional level because experiments are also managed by collaborations of research institutions and funded by national agencies. The rules for accessing, using and presenting the data and results are approved by the Collaboration Board, the main governing body of experiment, in which each institution has a representative with voting rights.

In general, access to the experiment is open to all research institutions from around the world, not just to the institutions from CERN member states. The application is approved or rejected by a democratic vote of the Collaboration Board. One of the main criteria is the added value that the candidate institution brings to the experiment in terms of operation, maintenance and upgrades. This model of funding experiments at CERN implies the dual position of institutions. In order to be able to use the equipment for scientific purposes, it must contribute to the operating costs and contribute to the modernization of the apparatus. At the same time, researchers from these institutions can participate in the scientific programme.

By providing resources for the operation of these facilities, the LRI CERN-CZ fulfills the role of a gateway, enabling the CZ particle community to access the data of experiments at CERN and thus enabling it to participate in unique scientific research at CERN. CERN-CZ is open to new Czech institutions wishing to participate in CERN projects. Together with VS CERN, it is ready to help and support these new candidates. The last example is the University of West Bohemia in Pilsen, which became a member of the TOTEM experiment in 2013 and technical associate institute of the ATLAS experiment in 2019.

Data on the size of the CZ and foreign user groups and usage of the LRI's resources are given in the following section I-C-II. Here, we provide a more detailed description of two major local facilities operated by the LRI that serve experiments at CERN.

***WLCG Tier-2 Data Processing Center***

LHC data processing is performed on the Worldwide LHC Computing Grid (WLCG) - a distributed infrastructure that connects computing and storage capacities from around the world. In the CR, we operate a Tier-2 center that supports the ALICE and ATLAS experiments. Most of the center resources are located at FZU, other computer servers are located at CU in Prague and part of storage capacities are located at NPI in Řež. Gradually, we renewed the hardware through investments from related OP VVV project and institutional sources. We share computing resources with other projects according to the ratio of financial resources delivered by these projects. This leads to virtually continuous maximum utilization of computing servers. Sharing disk capacity is not convenient because the data is stored for a relatively long time, but where possible, we use at least common databases and border servers, the so-called SE (Storage Element).

Users access the Tier-2 computing resources using grid tools. The end-user interface is experiment dependent. The ALICE experiment uses its own AliEn system, the ATLAS experiment uses the PanDa system for the distribution of computing tasks and Rucio for the data transfer and access. Each member of the experiment has access to the resources involved in the WLCG through these tools. At the end of 2019, the computing capacity of the Tier-2 center reached 8,000 computing cores, of which 5,000 were intended for the LRI CERN-CZ. HS06 units are used for a comparison of delivered computing power. The average power of our newer computing cores with HT on reaches 10 HS06 / core. Our official commitment to the ALICE and ATLAS experiments was 30,000 HS06 and 3,400 TB of disk space. We fulfilled these commitments, and in the case of delivered CPU power exceeded them significantly by using older hardware and minimizing downtime. Newly purchased computing clusters in 2018 and 2019 have a total capacity 33,360 HS06 dedicated for LRI CERN-CZ. In total, we delivered 605 million hours normalized per HS06 unit to WLCG in 2019. A year earlier it was 10% less. Usable capacity of disk servers from 2017 and 2018 reaches 2,800 TB, the rest is complemented by older servers. In 2019, in cooperation with CESNET, we increased our capacity of connection to the dedicated LHCONE network to 100 Gbps and to the public internet to 40 Gbps.

***Clean laboratory for testing of silicon particle detectors***

The new Clean laboratory for testing of silicon particle detectors has been built at FZU. The total area of this clean laboratory is 52 $m^2$. The class of laboratory cleanliness is ISO 7 according to ISO 14644-1 standard. The clean laboratory is also completely ESD safe. The laboratory infrastructure consists of the changing room with laminar air flow, technical corridor and technical room.

The most important measurement instrument present in the laboratory is the so called probe station, which enables us to contact the individual testing pads of the studied samples and perform the required electrical tests on these samples. Currently, the clean laboratory is equipped with two of these probe stations, the older one Karl Suss PA 200 and the completely brand new one Tesla 200 mm. The mechanical properties of the strip silicon sensors are measured with the OGP SmartScope CNC 500 metrology station. When the sensors are not measured, they are stored in the special dry storage cabinet MP Dry Cabinet IV ST, in which the inert nitrogen atmosphere and the relative humidity below one percent is kept. Electrical characteristics of irradiated sensors need to be tested at temperatures below -20 °C to avoid uncontrolled changes in the structure of silicon

damaged by the irradiation. For testing at low temperatures, the special cold testing setup can be used, when the tested samples are wire bonded on the dedicated testing structures by using either the automatic wire-bonding station F&S Bondtec Series 58XX or the manual wire-bonding machine Delvotec 5330. The wire-bonded samples are then tested either in the freezer or in the environmental chamber Binder MK 56.

Electrical characteristics of the irradiated sensors can be measured also in the probe station Tesla 200mm, which is able to cool down the sample to the temperature reaching -55 °C. The experimental equipment of the laboratory includes also several measurement devices, from which the most important are Source Measure units Keithley 2657A, Keithley 237, Keithley 2410-C, Keithley 2611A, Keithley 248 and TTi CPX400SP 420, LCR meters Wayne Kerr 6440B and HP (Agilent) 4284A, as well as switching systems Pickering and Keithley 7001 with the switching cards Keithley 7036 and Keithley 7153. Electrical characteristics of the silicon sensors are measured also with the very precise multimeters Keithley 6517A, Keithley 6517B, Keithley 487 and Keysight 34401A. Analogue and digital signals can be analyzed by using the oscilloscope Tektronix MSO 70404.

Distribution of electric field in silicon sensors, as well as their detection performance, can be newly studied also by using the special laser Edge-TCT setup. For the regular work in the laboratory the distribution systems for the pure and dry compressed air, nitrogen and vacuum need to be present. The required media are produced by the oil-less compressor Renner SLDK-S 7.5, nitrogen generator IMT PN OnTouch 1250 OV and oil-less vacuum pump SCROLLVAC 15 plus 1-ph. All these three machines are located in the technical room of the laboratory.

The cleanliness level of the laboratory is continuously monitored by the laser-based particle counter Kanomax model 3887. To prepare samples for the shipment the machine Komet PlusVac 20 is used, which enables us to position a sample into the ESD safe bag, vacuum all the air out of the bag and seal the bag opening by the heat sealer.

II. Describe the structure of LRI´s users, the range of their scientific specialization, stratification by their affiliation (universities, public research institutions, industry). Indicate number of users from the Czech Republic and from abroad.

The Czech user community of experiments at CERN, and thus the users of the LRI CERN-CZ services, had 258 members at the end of 2018. Experiments with the largest Czech participation are ATLAS (approx. 140 users from 4 institutions), ALICE (approx. 30 users from 2 institutions) and COMPASS (approx. 30 users from 2 institutions). The Czech community consists of about 40% of researchers (including post-doctoral students), 20% of doctoral students, 15% of Master's and Bachelor's students, and 25% of engineers and technicians.

The international community of the LRI CERN-CZ users is very broad due to the strongly international nature of research at CERN. The two largest experiments with CERN-CZ involvement have alone nearly 5,000 members, as measured by the number of publishing authors. The ATLAS experiment has about 3000, and the ALICE experiment has about 1900 publishing members. Typically one third of them are PhD students, one third are junior researchers (post-doctoral students) and one third are senior researchers. Both the Czech and the international communities are stable in time, showing a slight increase in the number of members in 2016-2019. In the following years, we expect a similar use of LRI CERN-CZ as before.

Both communities use also directly the resources of the computer center operated by CERN-CZ. It serves as a Tier-2 center in the hierarchy of CERN computing grid. Users have access to the computing capacity of the center through standard WLCG tools. The results of the Tier-2 data processing and detector simulations are available to all members of the supported ALICE and ATLAS experiments. More than 1,000 individual users have used our resources every year for their individual analyses of experimental data.

III. Provide an overview of workshops, conferences, seminars and meetings organized by the LRI, incl. the number and affiliation portfolio of participants from the Czech Republic and abroad.

**2016**

- Student workshop on "Heavy ion physics", 5-6 October 2016, Prague. 21 participants, one from abroad (the speaker). Affiliation of participants - FZU: 6, CU: 4, CTU: 6, NPI: 2, UPOL: 2, Ecole Polytechnique, Paris: 1
- Traditional meeting of CZ High Energy Physics (HEP) community dedicated to the discussion about the future of the field, 14 December 2016, Prague. 67 participants, affiliations: 22 (FZU), 17 (CU), 17 (CTU), NPI (8), UPOL (2), Silesian University (1)

**2017**

- ATLAS CZ-SK Meeting, 2017, Praha - regular meeting of Czech and Slovak users of experiment ATLAS, 50 participants - 40 from the CR (14 FZU, 13 ČTU, 8 CU, 5 UPOL), 10 from the Slovak Republic (6 Comenius University, 4 Slovak Academy of Sciences)
- The 17th conference on Elastic and Diffractive scattering, EDS Blois 2017, Prague, 26-30 June 2017, 81 participants, the list with their affiliations can be found here: https://indico.cern.ch/event/577066/registrations/participants
- Traditional meeting of CZ High Energy Physics (HEP) community dedicated to the discussion about the future of the field, 12 December 2017, Praha. 68 participants, affiliations: 17 (FZU), 21 (CU), 18 (CTU), NPI (9), UPOL (2), Lund University (1)

**2018**

- 3rd Face-to-Face meeting of the ATLAS ITk Strip testbeam and irradiation group, 11-13 April 2018, Prague, 15 participants, from them 12 from abroad. Affiliations: 1 (FZU), 2 (CU), 2 (Instituto de Fisica Corpuscular), 2 (DESY), 2 (Albert Ludwigs Universitaet Freiburg), 2 (Carleton University), 1 (Technische Universitaet Dortmund), 1 (University of Birmingham, 1 (University of Toronto), 1 (IHEP, Chinese Academy of Sciences: Xiaocong Ai). Internal web page of the meeting: https://indico.cern.ch/event/709062/overview
- Special meeting of Czech and Slovak HEP community dedicated to the discussion about preparation of document of new European Strategy in particle physics for CERN Council, 14 September 2018, Prague, 57 participants, out of them 6 from the SR. Affiliations 16 (FZU), 13 (CU), 13 (CTU), NPI (7), UPOL (2), Pavol Jozef Safarik University in Bratislava (1), IEP SAS Kosice (2), UK Bratislava (2), IoP SAS Bratislava (1)
- Student workshop on "Standard Model and QCD", 8-9 October 2018, Prague, 20 participants, one, the lecturer, from abroad. Affiliations: FZU (6), CU (4), CTU (7), NPI (2), UPOL (1), Lund University (1)
- AFP ToF meeting, 6-7 December 2018, Praha. The ATLAS meeting dedicated to the construction of time-of-flight (ToF) detector for AFP detector of forward protons, 16 participants, out of the 6 from abroad. Affiliations: FZU (1), CU (1), CTU (2), UPOL (5), WBU

in Pilsen (1), INFN Bologna (1), INP PAN Krakow (2), U Alberta (1), Stony Brook U (1), DESY (1)

- Traditional meeting of CZ High Energy Physics (HEP) community dedicated to the discussion about the future of the field, 17 December 2018, Prague, 68 participants, affiliations: 22 (FZU), 15 (CU), 23 (CTU), 5 (NPI), 2 (UPOL), UK Bratislava (1)

**2019**

- Special meeting of Czech and Slovak HEP community dedicated to the discussion about new European Strategy in particle physics, 21 May 2019, Prague, 41 participants, out of them 3 from the SR. Affiliations: 11 (FZU), 10 (CU), 11 (CTU), 4 (NPI), 2 (UPOL), IEP SAS Kosice (2), UK Bratislava (1)
- ATLAS Tau Workshop, 3-7 June 2019, Prague. The ATLAS meeting dedicating to the physics of tau lepton, 59 participants, out of them 7 from the CR. Affiliation of participants from abroad: University of Toronto, Nanjing University, Chinese Academy of Sciences, The Hong Kong University of Science, Shanghai Jiao Tong University, Univ. of Valencia and CSIC, Albert Ludwigs Universitaet Freiburg, University of Bonn, Georg August Universitaet Goettingen, Technische Universitaet Dresden, Max-Planck-Institut fur Physik, Institute of High Energy Physics, Università degli Studi e INFN Milano, University of Bergen, IFIN-HH, Yale University, Lancaster University, Tel Aviv University, University of Oklahoma, Deutsches Elektronen-Synchrotron, CERN, NIKHEF, University of Sheffield. Internal web page of the meeting with the list of participants: https://indico.cern.ch/event/798098/registrations/participants
- ALICE Physics Week, 22-26 July 2019, Prague, meeting of experimentu ALICE dedicated to the physics analysis of the dataz, 154 participants with vast majority from abroad. The list, including the affiliations, is available on the web pages of the meeting: https://indico.cern.ch/event/798098/registrations/participants
- n_TOF Collaboration Meeting, 2019, Praha - Annual meeting of whole n_TOF Collaboration, 65 participants, out of them 2 from the CR, the rest were representatives from n_TOF institutes across the whole world (mostly Europe)
- Special meeting of Czech and Slovak HEP community dedicated to the discussion about new European Strategy in particle physics, 17 October 2019, Prague, 25 participants, out of the 2 from the SR. Affiliations: 7 (FZU), 6 (CU), 6 (CTU), 3 (NPI), 1 (UPOL), IEP SAS Kosice (1), UK Bratislava (1)

## D. Linkages to Other Infrastructures and Projects, Internationalization

I. Describe established and running cooperation within the Czech Republic with research institutions, research infrastructures, industry and other entities utilizing the LRI or its results. If applicable, provide a list of agreements with cooperating entities (collaboration agreements, contracts, memoranda etc.).

CERN-CZ organizes and supports the participation of universities and research institutions from the CR on projects in the international laboratory CERN. All Czech research institutions, which substantially participate in the operation and construction of experiments at CERN, are members of the LRI. Within the framework of CERN-CZ, they cooperate together on the fulfilment of the

international obligations arising from their membership in CERN projects (see the following chapter I-D-II).

CERN-CZ cooperates with other LRIs in the area of informatics and large data processing.

The LRI CESNET, the Czech national provider of research and education network, provides 10 Gbps dedicated network connectivity between computer clusters and disk servers of Prague WLCG Tier-2 located at FZU, NPI and CU. CESNET also connects the main Tier-2 resources at FZU to LHCONE network via a dedicated link. This link was upgraded in 2019 from 2x10 Gbps to 100 Gbps and is adequately utilized. A remote backup of critical data is another important service provided by CESNET. CESNET also serves as National Grid Initiative and represents the Czech Republic in the European Grid Initiative EGI. EGI monitors our resources and collects usage statistics.

The national supercomputing center IT4I in Ostrava provides a significant fraction of the Czech computing capacity for the ATLAS experiment. In case of temporarily free nodes on Anselm or Salomon supercomputers we can automatically resubmit waiting jobs from the Tier-2 to these distant capacities and later transfer results back to the WLCG Storage Elements. We also tested a system of continuous output upload by individual simulated events which enables job termination when another task with higher priority is submitted. This enables usage of short term free capacities and increases the average usage.

We also closely collaborate with LRI AUGER-CZ, CTA-CZ and Fermilab-CZ on purchase and operation of computer and disk servers.

Czech industry was also involved in the fulfillment of our obligations towards CERN experiments, see Section II-C-I. Examples of cooperation with industry at various stages of implementation are:

- Unicorn College - production database for components of Inner Tracker detector (ITk) for ATLAS HL-LHC upgrade (expected volume of 350,000 CHF, i.e. about 8.4 million CZK),
- Argotech - wire-bonding of silicon sensors for ITk tracking detector for ATLAS HL-LHC upgrade (expected volume of 5-7 million CZK),
- UJP Praha a. s. - cobalt source irradiation campaign for the purpose of radiation tests of ITk components (expected volume of 600,000 CZK),
- Crytur - development of new scintillation materials for experiments at CERN (in 2019, one contract for scintillation fibers worth of 48,000 EUR, i.e. about 1.2 million CZK was obtained from CERN for the LHCb experiment),
- Foton - development of power supplies for experiments at CERN (in 2017, delivery of high voltage power supply prototype for the ATLAS experiment, price 25,000 EUR, i.e. about 600,000 CZK; ATLAS chose at the end a different system to power supply the TileCal photomultipliers).

II. Describe established and running cooperation with international and foreign research institutions, research infrastructures, industry and other entities utilizing the LRI or its results. If applicable, provide a list of agreements with cooperating entities (collaboration agreements, contracts, memoranda etc.).

Experimental research in particle physics is concentrated in a relatively small number of world laboratories. This strategy is dictated by the high demands on human and financial resources that are necessary for the construction and operation of experimental facilities for research at the

highest particle energies available in earth laboratories. Intensive international cooperation of CERN-CZ is therefore a necessity. Within the two CERN experiments with the largest CZ participation, CERN-CZ cooperates with more than two hundred research organizations. The ATLAS experiment is operated and used by about 3000 scientists from 183 laboratories and research institutions from 38 countries, of which 4 are from the CR from LRI CERN-CZ (the list of ATLAS institutions is available at http://atlas.web.cern.ch/Atlas/Management/Institutions.html). Overall, Czech teams represent about 2% of the ATLAS experiment in terms of the number of scientists on ATLAS author list. In the case of the ALICE experiment, the numbers are similar. The experiment is run and used by more than 1500 scientists from 154 laboratories from 37 countries (see http://aliceinfo.cern.ch/Public/en/Chapter3/Chap3Collaboration-en.html). The two Czech institutions represent about 1.5% of ALICE. In the case of smaller experiments, such as COMPASS or TOTEM, our participation is generally larger, and Czech groups represent up to 10% of the experiment.

Our participation in CERN experiments is legally framed by the membership of the Czech Republic in the international organization CERN. CERN membership fees are used to cover the operation of the laboratory and to build and develop basic infrastructure, such as buildings, computing resources, or major scientific facilities. In the last 25 years, some of the most valuable devices have been accelerators such as the Large Hadron Collider (LHC).

Membership fees of the CR are paid directly by the MEYS, they are not part of the CERN-CZ budget. This is related to the legal status of CERN. The states, and not individual research institutions, join this international organization. Charges are determined annually on the basis of the development and strength of the economies of each member state, as measured by the country's gross domestic product. The CR contributes about 1% to the CERN budget, which represents an annual amount of 10-11 million Swiss francs (CHF). In 2019, the CR membership fee was 10,860,850 CHF.

CERN membership allows the CR to participate in the management of the laboratory as described in the previous chapter I-B-I. It also grants full access of Czech research institutions to the experiments and projects at CERN. Last but not least, it enables Czech companies to apply for industrial contracts announced by CERN. They often make use of this possibility, typically Czech companies receive at CERN contracts at the level of 50-100 million CZK annually, see section II-C-I.

CERN experiments and projects are organized, operated and built by a large number of collaborating research institutions, and they are funded by national funding agencies. Formally, each institution's commitment is defined by the relevant MoUs related to the construction, operation and upgrades of scientific facilities. By signing the MoU, the national funding agencies confirm this commitment. In the case of the CR, the MoUs for larger and longer-term commitments are signed by the authorized representative of the MEYS. One of the main tasks of LRI CERN-CZ is to ensure fulfilment of these obligations.

The annual running costs of the LHC experiments are approved by representatives of the national funding agencies at the October LHC RRB meeting. They are then budgeted among the participating institutes on the basis of the key specified in the relevant MOUs. In the case of the ATLAS experiment, the typical annual contribution of CZ institutions to the running costs of the experiment is around 320,000 CHF (MoU document CERN-RRB-2002-035). For the ALICE experiment, it is around 105,000 CHF (document CERN-RRB-2002-034). Altogether, for all experiments and CERN RD projects, this represents a total annual commitment of CZ institutions

at the level of 520,000 CHF. The MoUs do not contain only financial commitments. It is also obligatory to provide the necessary manpower for the detector operation in the form of shifts during data acquisition and in the form of support of experts on individual detector subsystems (so called on-call experts). In 2018, researchers from CERN-CZ served 790 shifts for ATLAS and 130 shifts for the ALICE experiment. This is an equivalent of about 3.7 FTE. The ATLAS experiment also keeps track of additional technical work related to the operation and maintenance of the experiment. In 2018, the CERN-CZ institutions contributed in total 10.3 FTE to this type of work. Here the 2018 figures are given because the 2019 figures were not available at the time of writing. Figures for other years are available in the interim annual reports.

Other important documents are Memoranda of Understanding on the construction and upgrades of detectors. In the case of LHC experiments, these are mainly connected to the HL-LHC upgrade. They represent a significant commitment of the Czech institutions and LRI CERN-CZ to the ATLAS experiment. The CORE cost of ATLAS HL-LHC upgrade was agreed on by the LHC RRB at the level of 270 million CHF. Of this, the share of Czech institutes is 2.2%, i.e. approximately 6.1 million CHF. This commitment was partially covered from the CERN-CZ resources in 2016-2019. The remaining part will be covered from CERN-CZ budget in the years 2020-2022. The CORE costs cover only the construction costs, they exclude labour, development, and other indirect costs. CERN-CZ also contributed from its budget to these non-CORE costs. In 2018, the ATLAS experiment began to record the manpower provided by member institutions for detector modernization. ATLAS registered in 2018 the contribution of 10.9 FTE from the CERN-CZ institutions.

The level of our involvement is defined in the corresponding MoUs for upgrades of particular subsystems of ATLAS detect. During the duration of the project, the MEYS signed MoU for the strip part and common parts of the ITk tracking detector (document CERN-MoU-2019-018), the Tilecal calorimeter (document CERN-MoU-2019-020), and trigger and data acquisition system (TDAQ, CERN-MoU-2019-017). In early 2020, the MEYS signed MoU for the upgrade of the pixel part of ITk (document CERN-MoU-2019-227). In addition, MoU for the common parts of all subsystems (CERN-RRB-2017-058) was signed in 2017. In this case, our commitment is 510,000 CHF (with about 57,000 CHF paid annually for 9 years).

The largest contribution of LRI CERN-CZ to the HL-LHC upgrade of the ATLAS detector is the ITk detector. In the case of the strip part, we are committed to testing the strip sensors for one half of the end-cap part and modules assembly for one end-cap disc. We also contribute to the purchase of detector components like sensors, electronics, cables, etc. CERN-CZ also cooperates on the development of cooling and mechanical components of ITk. Important is also our support to the development of production database for the individual ITk components. The contract on the development of production database was received by the Czech university Unicorn College also thanks to the intensive support from the LRI. ITk CORE costs for the construction of the strip part are estimated to 60,638 thous. CHF as specified in the corresponding MoU. Commitments of CZ institutions are 2,700 thous. CHF. For common ITk parts, our commitment is 454 thous. CHF out of estimated total cost of 14,504 thous. CHF. In the case of pixel part of ITk, CZ institutes committed to cover 1,401 thous. CORE costs out of 48,902 thous. CHF. Our total contribution to the construction of the ITk detector is 4,555 thous. CHF out of 124 million CHF total CORE costs.

In the case of the hadronic calorimeter TileCal, we made in the MoU a commitment to support the upgrade of the hadronic calorimeter by 527 thous. CHF out of the expected total cost of 11,604

thous. CHF. The contribution is directed to the low voltage power supplies and to the system for distribution of high voltage for photomultipliers.

In the case of TDAQ MoU, we are committed to support the upgrade with 500 thous. CHF out of the total expected costs of 44,525 thous. CHF. The contribution goes into the purchases of readout electronics for ITk and for higher level trigger hardware.

CERN-CZ is involved in ALICE upgrades at similar level. MEYS signed two MoUs related to the upgrade of the ITS tracker detector with total commitment of 457 thous. CHF. This amount has already been fully covered from the CERN-CZ budget in years 2016-2019. In 2019, MEYS signed two additional MoUs for the construction of a forward muon tracker detector MTF (CERN-MoU-2019-056) amounting to 200 thous. CHF and for the upgrade of the readout and trigger electronics FDD (CERN-MoU-2019-057) with commitment of 260 thous. CHF. CERN-CZ covered from its budget 150 thous. CHF in 2019. The remaining part, 310 thous. CHF, will be covered from the LRI 2020-2022 budget.

***Relationship within the European Research Area***

There is a close relationship between European Union (EU) and CERN. The European Union obtained Observer Status in 1985, and is represented at the open sessions of the CERN Council by the European Commission. The relations between CERN and the European Commision are based on Administrative Arrangement for Scientific and Technological Cooperation, signed in 1994. A new Memorandum of Understanding between CERN and the European Commission was signed in July 2009 with the aim to further enhance the cooperation between the two institutions. This memorandum has also led to closer cooperation between CERN and ESFRI (European Strategy Forum on Research Infrastructures).

Fulfilling one of its principal roles, CERN organises European research in particle physics, and naturally plays a significant role in constituting the European Research Area in this field. The RI CERN-CZ represents a gateway through which Czech institutions are contributing to the shaping of this research are.

Following the special status of CERN as an international organization, ESFRI recognizes the leading role of CERN in the formulation of the European Strategy for Particle Physics. The last document on the strategy was approved by the CERN Council in 2013. Update of the Strategy is being prepared for the approval in 2020. One of the main priorities in the 2013 Strategy, a full exploitation of LHC scientific potential, was adopted by ESFRI and HL-LHC upgrade of experiments ATLAS and CMS is a landmark project in ESFRI 2016 Roadmap (p. 77).

III. Provide number of international research grants connected to the LRI, with a brief description and financial volume.

Project AIDA-2020 (http://aida2020.web.cern.ch/) within EU programme Horizon-2020 aims at the development and testing of new detector technologies. The project is coordinated by CERN. Duration: 2015-2020, budget: 12,909,986.73 EUR (EU contribution 10.0 mil. EUR), part concerning FZU: 145 thous. EUR (with contribution of 65 thous. EUR from EU).

# PART II. - OUTCOME

## A. Scientific Outcome Achieved

I. Describe generally scientific results achieved by the LRI's research team on the basis of the LRI's use over the funding period.

This section describes the results obtained by the CERN-CZ team regarding the activities on operation and development of the research infrastructure. Members of the LRI team are also involved in physics research on experiments at CERN that are operated with the help of CERN-CZ. They are co-authors of more than 630 original results published by the CERN experiments. These results are presented in the following section II-A-II. The selection of articles [4-20] in section II-A-II is a selection of physics topics and results, to which CERN-CZ team members contributed directly as the main authors of published analyzes.

Activities related to the development of the LRI can be divided into two categories:

- operation-related work,
- work related to the upgrade and construction of new detectors, and development of new technologies for future detectors.

The LRI's authors published in total 58 articles in these two categories. A complete overview is given in the annual interim reports. Here we provide just a selection of 19 papers documenting the different categories of research connected with the LRI development.

***Operation of detectors***

These activities are primarily related to the operation of those parts of the apparatus that CERN-CZ institutions helped to build, such as the ATLAS Inner Detector [1] and the TileCal calorimeter [2], or the operation of the monitoring system for data acquisition, which was built in recent years by CERN-CZ for the COMPASS experiment [3]. Further publications concern the calibration of these detectors [4-5] or deal with the operational support of data processing in the LRI's Tier-2 computer center [6].


[1] ATLAS Collaboration, *Performance of the ATLAS Transition Radiation Tracker in Run 1 of the LHC: tracker properties*, JINST 12 (2017) no.05, P05002

[2] ATLAS Collaboration, *Operation and Performance of the ATLAS Tile Calorimeter in LHC Run 1*, Eur. Phys. J. C78 (2018) 987

[3] O. Šubrt et al., *The Continuously Running iFDAQ of the COMPASS Experiment,* CHEP 2018, Computing in High Energy and Nuclear Physics, 9 - 13 July, 2018, Sofia, Bulgaria, EPJ Web Conf. 214 (2019) 01032

[4] M. Sabaté-Gilarte, at all. (n_TOF Collaboration), *High-accuracy determination of the neutron flux in the new experimental area n_TOF-EAR2 at CERN*, Eur.Phys.J. A53 (2017) no.10, 210

[5] ATLAS Collaboration, *Electron and photon energy calibration with the ATLAS detector using 2015–2016 LHC proton-proton collision data*, JINST **14** (2019) no.03, P03017

[6] M. Svatos, J. Chudoba, P. Vokac, *ATLAS utilisation of the Czech national HPC center*, EPJ Web of Conf. **214** (2019) 03005

***Detector upgrades and new technologies for future detectors***

Results in this category deal with topics related to the CERN-CZ core activities and international commitments. This mainly involves the detector upgrades in connection with HL-LHC upgrade of LHC, either by contributing to the detector design in the form of Technical Design Reports [7] or by specific aspects of construction, such as component testing for the ATLAS and ALICE upgrades on test beams [8-9] or other irradiation facilities [10]. The development of components for new tracker detectors takes place also within in the CERN Research & Development (RD) projects, where CERN-CZ is involved in RD50 (development of radiation-hard semiconductor sensors) and RD53 (development of radiation-hard readout electronics for semiconductor sensors). Another important class of work is the certification of materials for detector construction. For example, work [11] also has an impact on industry, as the requirement for radiation-hard materials is also connected with the energy industry, namely the safety of nuclear power plants.

Another part of the research concerns upgrades of current detectors. These are for example forward proton detectors of experiments TOTEM and ATLAS. In both cases, the CERN-CZ teams are involved in the development and construction of electronics and time-of-flight detectors with high-resolution timing at the level of several tens of picoseconds [12-16].

Furthermore, CERN-CZ researchers contribute with their expertise to solving the technical problems with detector cooling [17].

CERN-CZ contributes as well to the development of new scintillation materials for particle detectors [18] within the CERN CrystalClear project (former RD18). CERN-CZ closely cooperates on this with the Crytur, Ltd.co in Turnov. In 2019, this company obtained a contract from CERN for the production of scintillation fibres GGAG: Ce and YAG: Ce.

The CERN-CZ team is also involved in the development of industry applications of new technologies developed for particle detectors. An example is the use of Timepix sensors and chips [19] developed within the CERN Medipix and Medipix3 projects. There are many interesting applications, like radiation monitoring (e.g. on satellites), or applications based on sensors of various kinds of particles (photons, neutrons, ...) with high spatial resolution for use in medicine, biology, art-restoration, etc.


[7] The ATLAS Collaboration, *Technical Design Report for the ATLAS Inner Tracker Strip Detector*, CERN-LHCC-2017-005, ATLAS-TDR-025, CERN (2017)

[8] A. J. Blue et al., *Test beam evaluation of silicon strip modules for ATLAS phase-II strip tracker upgrade*, Nucl. Instrum. Methods Phys. Res. **A 924**, 108 (2019). https://doi.org/10.1016/j.nima.2018.09.041

[9] S. Kushpil, F. Krizek, A. Isakov, *Recent Results From Beam Tests of the ALPIDE Pixel Chip for the Upgrade of the ALICE Inner Tracker*, IEEE Transactions on Nuclear Science **66** (2019) TNS-2319-2323

[10] F. Krizek et al. *Irradiation setup at the U-120M cyclotron facility Nuclear Inst. and Methods in Physics Research*, A 894 (2018) 87–95.

[11] Kučera J, ..., Ferencei J et al., *Determination of elemental impurities in polymer materials of electrical cables for use in safety systems of nuclear power plants and for data transfer in the Large Hadron Collider by instrumental neutron activation analysis*, J. Radioanal. Nucl. Chem. 309 (2016) 1341

[12] J. Lange, M. Carulla, E. Cavallaro, L. Chytka, P.M. Davis, D. Flores, F. Förster, S. Grinstein, S. Hidalgo, T. Komarek, G. Kramberger, I. Mandić, A. Merlos, L. Nozka, G. Pellegrini, D. Quirion, T. Sykora, *Gain and time resolution of 45 µm thin Low Gain Avalanche Detectors before and after irradiation up to a fluence of $10^{15}$ $n_{eq}/cm^2$*, JINST 12 (2017) P05003

[13] Yu. Melikyan, T. Sýkora, T. Komárek, L. Nožka, D. Serebryakov, V. Urbášek, *Load capacity and recovery behaviour of ALD-coated MCP-PMTs,* Nucl.Instrum.Meth. **A949** (2020) 162854

[14] L. Chytka, M. Hrabovsky, K. Jirakova, T. Komarek, V. Michalek, L. Nozka, P. Schovanek et al., *Timing resolution studies of the optical part of the AFP Time-of-flight detector*, Optics Express 26(7), 8028-8039 (2018)

[15] TOTEM Collaboration, *Diamond Detectors for the TOTEM Timing Upgrade*, JINST 12 (2017) no.03, P03007

[16] R. Arcidiacono, M. Berretti, E. Bossini, M. Bozzo, N. Cartiglia, M. Ferrero, V. Georgiev, T. Isidori, R. Linhart, N. Minafra, M. M. Obertino, V. Sola, N. Turini, *Test of Ultra Fast Silicon Detectors for the TOTEM upgrade project*, JINST 12 (2017) no.03, P03024

[17] Vacek, V., Doubek, M.: *Problems in design of cooling systems for particle detectors and relevant electronics*, REFRIGERATION SCIENCE AND TECHNOLOGY PROCEEDINGS of the 25th IIR International Congress of Refrigeration, August 24-30, 2019 Montreal, Canada, 199-206, ISBN: 978-2-36215-035-7 (ISSN: 1025-9031)

[18] P. Průša, M. Kučera, V. Babin, P. Brůža, D. Pánek, A. Beitlerová, J.A. Mareš, M. Hanuš, Z. Lučeničová, M. Nikl, T. Parkman, *Garnet Scintillators of Superior Timing Characteristics: Material, Engineering by Liquid Phase Epitaxy*, Adv. Opt. Mater. 5 (2017) 1600875(1) - 1600875(9)

[19] A. Zhao, D. Byelov, Ch. Cheng, E. Maddox, P. Svihra, V. Vrba, T. Weinacht, *Coincidence velocity map imaging using Tpx3Cam, a time stamping optical camera with 1.5 ns timing resolution*, Rev. of Sci. Instr. 88, issue 11 (2017)

II. Describe main scientific results (max. 20) achieved by external LRI´s users on the basis of the LRI's use (its Czech node in case of distributed research infrastructures).

From the experiments supported by CERN-CZ (see the list in section I-A-I), the ATLAS experiment alone published more than 470 original papers in renowned international peer-reviewed journals in 2016-2019. During the same period, the ALICE experiment published more than 127 papers and other smaller experiments supported by CERN-CZ (COMPASS, TOTEM, MOeDAL, NA62, n_TOF) more than 40 papers. In total, there were more than 630 papers containing mostly new fundamental results in the field of elementary particle physics and nuclear physics.

Among the most interesting ones were two papers published in Nature Physics.

[1] ATLAS Collaboration, *Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC*, Nature Physics 13 (2017) 852–858

[2] ALICE Collaboration, *Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions*, Nature Physics 13 (2017) 535–539

The subject of paper [1] is the report from the ATLAS experiment about the first observation of light-by-light scattering. This process is forbidden in classical theory of electromagnetism (Maxwell's theory of electrodynamics). Light-by-light scattering is a purely quantum-mechanical

process connected with vacuum polarization. The existence of this rare phenomenon was among the first predictions of quantum electrodynamics (QED). The first evidence of this fundamental process was observed in ultra-peripheral collisions of lead nuclei at center-of-mass energy 5.02 TeV per nucleon recorded by the ATLAS detector at the LHC. The measured frequency of these collisions agrees with the QED predictions.

Interesting collective phenomena similar to those observed in heavy ion collisions have been unexpectedly observed in high multiplicity proton-proton collisions at LHC. The ALICE experiment reports in [2] the first observation of these collective phenomena also in enhanced production of multi-strange hadrons.

Other, widely cited results from CERN experiments include those that measure the properties of the Higgs boson, which was discovered by the ATLAS and CMS experiments in 2012. These include, for example, paper [3] on measurement of the Higgs boson production and decay rates from 2016 with a total of 407 citations (of which 106 are self-citations).

[3] ATLAS Collaboration, *Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at √s=7 and 8 TeV in the ATLAS experiment*, Eur. Phys. J. C76 (2016)

From a large number of publications, we presented a short selection of results from CERN experiments supported by CERN-CZ, to which scientists from CZ research institutions directly contributed as so-called primary authors. Practice in the field is such that experiment's papers are signed by all members of the experiment who have qualified as authors. One of the reasons is the high complexity of the detectors. It is extremely difficult to determine the contribution of an individual. Each analysis depends on the work of many other groups and could not be accomplished without them. The final result, however, originates in a narrower circle of primary authors of the analysis. Selected papers [4-20] document the activity of Czech users and show that Czech physicists make great use of the possibilities offered by the work on international experiments at CERN.

[4] ATLAS Collaboration, *Measurement of the exclusive γγ → μμ process in proton-proton collisions at 13 TeV with the ATLAS detector, ATLAS Collaboration*, Phys. Lett. B 777 (2018) 303

[5] ATLAS Collaboration, *Measurement of the inclusive jet cross-sections in proton-proton collisions at sqrt{s} = 8TeV with the ATLAS detector*, JHEP 1709 (2017) 020

[6] ATLAS Collaboration, *Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector,* Phys. Lett. B784 (2018) 173-191

[7] ATLAS Collaboration, *Measurements of ttbar differential cross-sections of highly boosted top quarks decaying to all-hadronic final states in pp collisions at s=13 TeV using the ATLAS detector,* Phys.Rev. D98 (2018) no.1, 012003

[8] ATLAS Collaboration, *Search for tetraquark in Bspi decays*, Phys. Rev. Lett. 120 (2018) 202007

[9] ATLAS Collaboration, *Measurement of charged-particle distributions sensitive to the underlying event in √s=13 TeV proton-proton collisions with the ATLAS detector at the LHC*, JHEP 1703 (2017) 157

[10] ATLAS Collaboration, *Measurement of jet fragmentation in Pb+Pb and pp collisions at sqrt(s_NN) = 2.76 TeV with the ATLAS detector at the LHC*, Eur. Phys. J. C 77 (2017) 37
[11] ALICE Collaboration, *Anisotropic flow of charged particles in Pb-Pb collisions at √sNN =5.02 TeV*, Phys.Rev.Lett. 116 (2016) no.13, 132302
[12] ALICE Collaboration, *Investigations on anisotropic flow using multi-particle correlations in pp, p--Pb, Xe--Xe and Pb--Pb collisions*, Phys. Rev. Lett. **123**, 142301 (2019)
[13] ALICE Collaboration, *Energy dependence of exclusive J/□ photoproduction off protons in ultra-peripheral p–Pb collisions at √□NN = 5.02 TeV*, Eur. Phys. J. C79 (2019) 402
[14] TOTEM Collaboration, *First determination of the rho parameter at sqrt(s) = 13 TeV: probing the existence of a colourless C-odd three-gluon compound state*, Eur. Phys. J. C79 (2019) 785
[15] TOTEM Collaboration, *Elastic differential cross-section measurement at sqrt(s) = 13 TeV by TOTEM*, Eur. Phys. J. C79 (2019) 861
[16] COMPASS Collaboration, *First measurement of transverse-spin-dependent azimuthal asymmetries in the Drell-Yan process*, Phys.Rev.Lett. 119 (2017) no.11, 112002
[17] COMPASS Collaboration, *Longitudinal double-spin asymmetry A(1)(p) and spin-dependent structure function g(1)(p) of the proton at small values of x and Q(2),* Phys. Lett. B 781 (2018) 464-472
[18] MoEDAL Collaboration, *Search for magnetic monopoles with the MoEDAL forward trapping detector in 2.11 fb$^{-1}$ of 13 TeV proton-proton collisions at the LHC*, Phys. Lett. B 782 (2018) 510-516
[19] NA62 Collaboration, *First search for K+ → π+νν using the decay-in-flight technique*, Phys. Lett. **B791** (2019) 156
[20] n_TOF Collaboration, *Be-7 (n,p)Li-7 Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN*, Phys. Rev. Lett. 121 (2018) no.4, 042701

## B. Compliance with the Project Plan

Describe all deviations and changes to the original plan of realization (in scope, objectives, personnel) over the course of realization period and explain their reasons.

CERN-CZ plans and strategy for future development are closely linked to the CERN plans and plans of individual experiments. From an operational point of view, these are mainly regular two-year long shutdowns of the LHC. During the project duration, the LHC was in operation in the years 2016-2018. This was a period of intensive data taking by the LHC experiments. Fulfilling the operation commitments was a high priority activity for CERN-CZ. A two-year long LHC shutdown (LS2) started in January 2019. It is focused on the collider maintenance and upgrade. At the same time, the LHC experiments undergo maintenance and upgrades as well. The LS2 plans were already known at the time of the project preparation in 2014 and the relevant activities of CERN-CZ were carried out in accordance with this plan. This mainly involved ensuring the operation of experiments during the data taking in the form of data taking shifts or by providing on-call experts for detector subsystems. In connection with the LHC shutdown in 2019, the aim was to provide

experts and technical staff for the maintenance and upgrades of experiments supported by CERN-CZ.

HL upgrade of LHC and LHC experiments are planned for the next LHC long shutdown LS3. At the time of the proposal in 2014, the LS3 was planned for years 2022-2024. It was postponed by CERN to years 2024-2026 in 2015. And at the end of 2019, it was moved further to years 2025-2027 due to large complexity of the upgrade projects and available resources. Participation on HL-LHC upgrades of experiments ATLAS and ALICE is together with detector operations a core activity of CERN-CZ. Due to the planned significant beam intensity increase in HL-LHC, it is necessary to substantially rebuild the detectors, in many cases their entire parts need to be replaced, see section I-D-II for the specification of CERN-CZ upgrade commitments.

The shift of LS3 in LHC schedule meant for LRI CERN-CZ the extension of the preparatory phase for the development and design of new detectors. The technical proposals for all the individual detector parts, in the upgrade of which Czech research institutions have been involved, were completed during the project period and the relevant memoranda of understanding on the construction of these detectors were signed by the grant agencies. The last memorandum for the HL-LHC project with Czech participation concerning the pixel part of the ATLAS ITk detector was signed by the MEYS in January 2020. The postponement of the start of LS3 was also used for the preparation of local CERN-CZ laboratories that will participate in the production of new detectors. This includes, for example, the Clean laboratory for testing of silicon particle detectors described above.

## C. Socio-economic Impacts

I. Impact on economy: Indicate number of jobs in the LRI for the entire period (researchers/other staff) and number and financial volume of contracts with industry concluded in the framework of public procurement to maintenance and renewal of the LRI.

The success of CERN in exploring the secrets of the micro-world using new technologies increases the attractiveness of educational and research institutions for students and experts, who then apply the acquired skills in companies and thus increase their innovation potential and competitiveness. Delivered orders and successful operation of a number of facilities built in the CR for CERN represent to industrial companies prestigious knowledge and technologically demanding orders that stimulate their innovation abilities. On average, Czech companies in CERN receive contracts with an annual volume in the range of 50 to 100 million CZK. The return rate for industrial orders (“Industrial return”) with a value of 1.80 in 2018 (average 1.46 in 2014-17) ranks the CR among the relatively most successful industrial suppliers from member countries.

Czech companies contributed significantly to the construction of LHC experiments (semiconductor detectors for ATLAS Inner Detector, power suppliers, vacuum and optical components, steel). HL upgrade of LHC and experiments represent further opportunities for them. Examples of new collaboration at various stages of implementation are companies like: Unicorn College (ITk component database), Argotech (silicone detectors), Nuclear Fuel Institute (detector irradiation testing), Crytur (scintillators), see section I-D-II. Examples of applications of technologies developed for CERN in the CZ industry are TimePix silicon detectors with applications in space industry, education and medicine, or scintillation detectors used in electron microscopy and tomography. Cooperation with industry and transfer of technologies developed at CERN to

industry should be intensified also due to the activity of the upcoming CERN incubation center in the CR.

***Public procurement for maintenance and renewal of LRI***

Resources of related OP VVV project "*CERN Computing*" were used to acquire computing clusters and disk servers for Tier-2 computing center. Their purchase was organized together with other OP VVV projects purchasing IT hardware in the following contracts:

- "*Computing Cluster for Projects Using Distributed Grid Computing Capacities*", year 2017, price 7,460,000 CZK with VAT (CERN-CZ share: 5,460,000 CZK), http://cern.ch/go/jd7R
- "*Storage capacity and accessories*", year 2017, price 3,480,300 CZK with VAT (CERN-CZ share: 2,860,000 CZK), http://cern.ch/go/wK7D
- *"Computing cluster for OP VVV projects 'CERN Computing' and 'Collaboration on Fermilab experiments'"*, year 2019, price 3,780,000 CZK with VAT (CERN-CZ share: 2,780,000 CZK), http://cern.ch/go/m8Ss

***Resources from LRI institutions***

The investment sources of the hosting and participating institutions were used to equip the Clean Laboratory for Testing Silicon Particle Detectors. There were three tenders for expensive equipment:

- Metrology station OGP SmartScope CNC 500, year 2017, source Czech Academy of Sciences (CAS), price 100,430 EUR,
- Probe Station Tesla 200 mm, year 2018, source CAS, price 1 836 982.08 CZK,
- Wire-bonding station F&S Bondtec Series 58, year 2019, source CAS, price 177,870 EUR.

In other orders, below the limit for tenders, the CAS invested to the laboratory's equipment additional amount of 4,193,291.48 CZK. The total amount invested in laboratory equipment was 23.3 million CZK.

II. Impact on educational activities: Estimate number of master and PhD students using the LRI´s data, trained in courses by LRI, new publications (textbooks) using LRI´s data.

Science and technology development provide motivation and perspective for education, stimulate curiosity, foster creativity, and also illustrate that results are not coming for free, but that they are redeemed by effort, time, money, figuratively speaking "sweat". All of this is needed by the education system, employers are calling for it, and CERN strongly supports it in many ways. In the corresponding research areas, the infrastructure provides access to world-class science for the entire academic world.

The services of CERN-CZ and data from experimental facilities supported by CERN-CZ were used in 2016-19 for defended qualification works at CU by 19 bachelors, 11 graduates and 8 doctoral students. There were 13 bachelors, 17 graduates and 11 doctoral defended students at CTU, 3 graduates and 2 doctoral students at UPOL, one doctoral student at TUL and one at UWB. This gives total figures of 32 bachelors, 31 graduates and 23 doctoral students that defended their works in reported period.

Teacher-centered LRI activities are mentioned in the PR section (Chapter IV-III).

CERN-related topics can also be found in students' works at schools and universities outside of the LRI. This illustrates the accessibility of CERN to the entire Czech environment.

Examples of doctoral thesis from non-LRI universities:

- Filip Mravec, Numerical Processing of Spectrometric Data. Masaryk University (MU) in Brno, Faculty of informatics, 2018,
- Pavel Kočí, Aspects of Supersymmetry and Supergravity. MU, Faculty of Science, 2019,
- Miroslav Novotný, Introduction to physics of microcosm. MU,Faculty of Science, 2017.

Examples of diploma thesis from non-LRI universities:

- Petra Dvořáčková, Standard Model Knowledge at Classroom. MU, Faculty of Education, 2016,
- Karolína Šupejová, The Creative Process Model of Sonification. MU, Faculty of Arts, 2019,
- Tomáš Michálek, Digital folklore. MU, Faculty of Arts fakulta,
- Šimon Evin, Alex Jones vs. the Globalists: Conspiracy Discourse in America Today. MU, Faculty of Arts, 2019,
- Lukáš Mocek, Has God his place in modern cosmology? UPOL, Sts Cyril and Methodius Faculty of Theology, 2018,
- Daniel Lešiga, System of Purchasing in International Research Organization. VSB - Technical University of Ostrava, Faculty of Materials Science and Technology, 2019

III. Other socio-economic impacts (in applicable): Impact on technology sphere and quality of life, other outputs in connection with the LRI's operation.

Because of the needs of experiments, CERN has contributed to developments in the fields of computer science and developments of detection and acceleration techniques. Perhaps the most widely known examples are the World Wide Web, developed in 1989 at CERN to improve the effectiveness of information exchange between scientists in large experiments, and transparent capacitive touch-screens developed at CERN in the early 1970's for the control room of accelerator SPS. Both technologies have had significant impact on our everyday's lives.

An important part of quality of life is the self-realization of an individual at work; CERN is a very remarkable illustration of the attractiveness of scientific and technical work on the edge of human knowledge, possibly giving an attractive vision for a certain specific part of the population. We received a very positive response from the public at the Colors of Ostrava 2019 festival, where we presented CERN and the opportunities it offers, see section IV-III on PR.

## D. Future Prospects (Outlook)

Describe the foreseeable future of the LRI´s facility, project team and expected further utilization of the results achieved. Describe intent of continuation, plans for future, intended grant applications etc.

***Expected future of LRI facility***

The hosting and participating institutions of LRI CERN-CZ are well-established research institutions with many years of tradition. These include leading Czech universities and institutes of the Academy of Sciences of the CR. As described above, all these institutions have strongly

supported activities of Czech groups at CERN, presently covered by the LRI CERN-CZ project, for more than 30 years. The same level of support can be expected in the future as long as CERN exists and is operated by its state members.

***Plans for the future***

The future plans of CERN-CZ are closely linked to the plans of CERN. Over the next 15 years, the main priority is the full exploitation of the LHC scientific potential by High Luminosity upgrade of the LHC machine. The main LHC experiments supported by CERN-CZ, such as ATLAS and ALICE, will remain operational throughout the entire period of operation of the LHC, i.e. at least until 2036.

LRI CERN-CZ already received support from the MEYS for the years 2020-2022. It will be financed under the same programme of Large Research Infrastructures as this ending project. As in this project, the investments will be financed from the associated OV VVV project, which was as well approved by the MEYS. In addition to supporting the operation of the experiments, the main LRI's priority will be HL-LHC upgrades of experiments. At this time, we expect the start of construction activities, as new detectors must be ready for installation during the LS3 LHC shutdown, scheduled for 2025-2027.

LHC experiments are long-term projects. The three CERN-CZ institutions are among the founding members of the ATLAS experiment, which was established in 1994. It is expected that the experiment will continue to process data several years after the closure of the LHC, at least until 2040. Therefore, we plan to apply for funding in the next LRI call for the period 2023-2029.

CERN has the ambition to maintain its world-leading role in particle physics even after the final shutdown of LHC. It has prepared technology for two possible options of future accelerator at CERN, either a linear electron and positron collider (CLIC) or a next generation circular collider (FCC). It has not yet been decided which path to take. Czech research institutions have a constant interest in participating in the world-leading CERN research programme and CERN-CZ institutions plan to expand their activities in the preparation of these new projects.

# PART III. – FINANCIAL EFFICIENCY

## A. Overview of Financial Costs in Total

| Spent recognised costs (in kCZK) | 2016 | 2017 | 2018 | 2019 | Total |
|---|---|---|---|---|---|
| Personnel costs | 7 130 | 7 270 | 7 410 | 8 450 | 30 260 |
| Investments | 0 | 0 | 0 | 0 | 0 |
| Membership fees | 38 921 | 34 251 | 33 661 | 33 340 | 140 173 |
| Operating costs | 33 482 | 29 333 | 29 917 | 29 335 | 122 067 |
| Refunded funds | 0 | 0 | 0 | 6 | 6 |
| **Total** | 79 533 | 70 854 | 70 988 | 71 131 | 295 006 |

I. Explain generally schedule and justification of usage of financial resources over the realization period, explain the total amount for main activities covered by funding provided, in a way that enables to assess overall financial efficiency of the LRI.

The CERN-CZ budget is based on the LRI strategy related to the short-term and long-term plans of CERN experiments. Full exploitation of LHC research potential is a main scientific priority. This results in two main tasks for our LRI. The first, coupled with a short-term strategy, is to maintain and support the operation of the experiments so that these experiments can record LHC collisions with high efficiency. This is linked directly to the financial support for operation and maintenance, which is paid by CERN-CZ in the form of membership fees. These are approved annually for individual experiments by the LHC RRB as described above. The CERN-CZ budget allocated adequate resources so that LRI's institutions could meet their commitments to the experiments. Financial contribution is only part of the institutional commitments. The institutions have to provide appropriate manpower for detector operation and maintenance - either in the form of shifts in the control room during data taking, on-call experts, or other technically oriented work. This drives the travel costs of the LRI. Part of the operational commitments is also operation of the computing center, which serves for the processing of experimental data and which is included in the hierarchy of the LHC grid network as a Tier 2 center.

The second task is of a longer-term nature and concerns the upgrades of experiments in connection LHC high luminosity upgrade (HL-LHC). In the case of the ALICE experiment, most of our contributions are linked to the current LS2 downtime. In the case of the ATLAS experiment, the CERN-CZ is mostly involved in the construction of detectors for HL-LHC. The new detectors must be ready for the installation in the next long LHC shutdown LS3 scheduled for 2025-2027. The commitments of CZ institutions are specified in more detail in the individual Memoranda of Understanding for the construction of new detector parts, see part I-D-II. The financial part of these commitments is paid in the form of a fee, either as one-off payments for smaller projects or interim and annual payments for larger projects. Part of the deliverables is in the form of supplies of detector components, which are being assembled in the LRI's local laboratories. This generates operating and investments costs connected with the running of these laboratories.

Both main tasks required adequate human and financial resources and were supported from CERN-CZ budget.

II. Elaborate on personnel costs, investments (if applicable), membership fees (if applicable), operating costs, explain briefly the main expenditures and changes between years in funded period. In operation costs elaborate on the kinds of expenditures (consumables, services, travel costs etc. – according to the table in Annex 1 of this report).

***Personnel costs***

On average, a manpower of approx. 11 FTEs was funded annually from the CERN-CZ budget. Additional manpower of approx. 13 FTEs was supported in the form of personal bonuses to the salaries provided by the LRI's institutions. The remaining personnel costs were also carried by the LRI's institutions.

For example, in 2018, the LRI funds were used to create 8.63 FTE in the form of main labour contract (HPP) in the total amount of 5,009 thous. CZK. A total amount of 612 thous. CZK was used to create additional 1.61 FTE (3 210 hours) in the form of work agreements (DPC) and side labour contract (DPP). An amount of 1 721 thous. CZK was used for personnel bonuses for employees whose salaries were covered by the LRI's institutions. These employees contributed to the operation of LRI with a total of 11.7 FTE.

The figures were similar in 2019. The LRI funds generated 9.90 FTE in the form of HPP in the total amount of 6 070 thous. CZK, and 1.51 FTE (3,017 hours) in the form of DPC/DPP in the total amount of 718 thous. CZK. An amount of 1 919 thous. CZK was used for personnel bonuses for employees whose salaries were covered by the LRI's institutions. These employees contributed to the operation of LRI with a total of 11.5 FTE.

A more detailed breakdown of personnel costs into different groups can be seen from the table in Part I-A-III and the detailed personnel cost statements in the annual interim project reports.

***Investments***

No investments were made from the LRI CERN-CZ budget in years 2016-2019. These were paid either within the associated OP VVV project "*CERN Computing*" project or directly from the resources of LRI's hosting and participating institutions. More detailed figures are available in part I-C-I.

***Membership fees***

Membership fees are of twofold characters: operating and maintenance fees and a contribution to the construction and upgrades of detectors. The operating fees are paid by the member institutions of each experiment. They are based on relevant MoUs and for LHC experiments they are reviewed and approved by the LHC RRB, details in section I-D-II. Membership fees paid from the LRI's budget were: 13.8 million CZK in 2016, 12.5 mil. CZK in 2017, 11.8 mil. CZK in 2018, and 11.5 mil. CZK in 2019. For the entire reported period 2016-2019, the membership fees for the operation and maintenance of CERN experiments and projects amounted to 49.6 mil. CZK.

Commitments for the detector upgrades have been described in detail in part I-D-II. In years 2016-2019, the LRI's budget covered 90.6 mil. CZK of CORE cost commitments for the detector upgrades. In the case of the ATLAS experiment, the total collected amount was 3,054 thous. CHF for HL-LHC upgrades and 180 thous. CHF for the construction of the AFP detector. In the case of

the ALICE experiment, the CERN-CZ contribution was 637 thous. CHF, 487 thous. CHF went to ITS, 100 thous. for FDD and 50 thous. for MTF. In addition, the CERN-CZ contributed to the upgrade of the MOeDAL experiment with amount of 30 thous. CHF.

***Operating costs***

The total operating costs for the reported period 2016-2019 amounted to 122 067 thous. CZK. Operating expenses are divided into the following main categories: travel, services, small tangible assets, consumables, and other indirect costs.

*Travel expenses* accounted for the largest part of the operating costs. They reflect the needs of individual experiments and serve to fulfil the CERN-CZ commitments towards the operation and maintenance of detectors for experiments at CERN. Retaining the LRI's experts at CERN is a key part of the services provided by the LRI. Other parts of travel expenses to CERN were related: to the participation in collaboration meetings related to the operation and management of the experiments; to the representation of the CR in the management and advisory bodies of CERN (CERN Council, Finance Committee, LHC RRB, etc.).

Total travel expenses amounted to 60 313 thous. CZK for the whole reported period, i.e. on average 15.1 mil. CZK per year. This roughly corresponds to an annual stay in CERN for about 12-13 people, excluding the transport costs. The equivalent of approx. 3 person-years was used to cover long-term stays for employees that were providing the key LRI's services directly at CERN. This involved the support for the operation and upgrades of detector components for which the CERN-CZ institutions are responsible for. Most of the funds were used for short-term stays at CERN concerning the detector operation during data acquisition, collaboration meetings and representation of CZ institutions and the CR in the governing bodies of CERN and CERN experiments. These figures correlate well with shifts and other operational support as reported by the experiment. For example, in 2018, a total of 930 shifts, an equivalent of 3.7 FTE, were served by the LRI's staff for the two LHC experiments, ATLAS and ALICE. The ATLAS experiment then accounted 10.3 FTE for additional technical contribution of CERN-CZ (provided mostly during stays at CERN) and 10.9 FTE for HL-LHC ATLAS upgrade (with smaller part provided at CERN), see part I-D-II.

A small part of the travel expenses was used for travels outside of CERN: collaboration meetings organized by a member institution outside of CERN; travels to other beam-test facilities; workshops enhancing the qualification and expertise of LRI staff; etc. Another part of travel expenses in amount of 589 thous. CZK included expenses for the stay of the LRI's invited guests. This included, for example, the reimbursement of the subsistence costs of the CERN-CZ Advisory Board members in connection with the annual Advisory Board meeting. Popularization and education were also supported by minor means in the form of covering part of the travel costs associated with popularization events at CERN (CERN Teacher Days, CERN Masterclasses, IPPOG, etc.).

*Services* in the total volume of 22 317 thous. CZK represented the second largest part of direct operating expenses. The largest part of services was related to the additional detectors operation and upgrade costs not covered by the MoU's membership fees. These include: contribution to the institutional fund of the ITk tracking detector being built, share of development costs for new

detectors as these are not part of CORE costs, etc. In 2019, the CERN-CZ supported from its budget the ATLAS experiment with 49 thous. CHF and a TOTEM experiment with 34 thous. CHF.

Services also included the energy costs. The electricity costs for the operation of the computer Tier2 center were covered from the LRI's budget in the total amount of 3 838 thous. CZK, i.e. annually approx. 960 thous. CZK. Another part of energy costs was covered from the budget of related OP VVV project and the rest was carried by the hosting institution. For example, in the last year of the project in 2019, the total computer center electricity costs amounted to 3 262 thous. CZK, of which the part related to the CERN projects represented 66%, i.e. 2 163 thous. CZK. Of this amount, 1 040 thous. CZK was paid from the CERN-CZ budget, 796 thous. CZK from the related OPVVV project "*CERN Computing*" and the remaining part was covered by the hosting institution.

Another part of the services consisted of: licenses for a dedicated software for sensor and reading electronics design; rental costs for apartments in the vicinity of CERN (long-term rental saves the LRI's travel costs); costs associated with organizing collaboration meetings; Advisory Board meetings; etc.

*Consumables and small tangible assets* in total amount of 13 929 thous. CZK accounted for the smallest part of direct operating expenses. These were mainly laboratory instrumental and material equipment of non-investment nature and upgrade of computer equipment, whether personal desktops and laptops for LRI employees or upgrades of Tier-2 computing center equipment of non-investment nature (like hard-drives, etc.).

*Overheads* reflect the indirect costs associated with the operation of the LRI. They do not apply to investments, membership fees and energy costs. The hosting institution's overhead costs were determined using the Full Cost method. The cost analysis was carried out in cooperation with Deloitte Advisory Ltd. and is specified in the Decision of the Director of the Institute of Physics of the CAS, v. i. i., No. 300/2012. Subsequently, the entire procedure and methodology was audited by BDO CA Company, ltd. The overhead costing was updated every year according this methodology. Similarly, the overheads of the partner institutions were determined in accordance with the institutional internal rules. The total overhead costs of LRI in the supported period amounted to 25 511 thous. CZK. This represents 14.8% of the total operating and personnel costs or 8.7% of the total project costs.

III. Describe briefly amount and reasons of returns (refunded funds) in particular years (differentiate funds returned in the year or within final financial settlement).

In the reported period, practically the entire subsidy was spent. Only in 2019, due to an accounting error, which was discovered at the beginning of 2020, a small amount of 5 590.13 CZK in the category of Membership fees was not used. These funds were returned to the MEYS.

## PART IV. – ADDITIONAL RELEVANT INFORMATION

| Calls for Tenders, Gender Issues, Outreach |
|---|
| I. Provide an overview of calls for tenders pursuant the Act No. 134/2016 Coll., on Public Procurement, list of contracts concluded with suppliers and service providers. |
| There were no calls for tenders pursuant according to the Act. No. 137/2006. All contracts and orders were of smaller volumes below the limit of the Act. Responsible scientists for the participation of hosting and participating institutions in the LRI CERN-CZ were following the internal rules of their home institutions for all contracts and orders. |
| II. Describe the LRI´s approach to gender issues within the project, gender composition of core team, the policy that has been applied to enable equal opportunities within the core team. |
| The LRI CERN-CZ is not an independent legal entity and is bound to follow the rules and policies of its hosting and participating institutions, including gender policy. The CERN-CZ's institutions are well-established research and academic institutions - universities and institutes of the Czech Academy of Sciences (CAS). Equal access to collaborators and students is an integral part of the working culture at these institutes. For example, it is embedded in the Code of Ethics for Researchers of the CAS, which in Article IV, part a) says<br><br>*"[Researcher] admits students and research co-workers after objectively evaluating their intellectual, ethical and personal characteristics",*<br><br>or in the Code of Ethics of Charles University, where it stands in Article 18, Part 1 the<br><br>*"They [members of the academic community and employees] refuse discrimination on the grounds of race, ethnic origin, nationality, ideology, religion, faith, world view, age, gender, sexual orientation, physical handicap, language, social origin, or property. They treat everybody with respect, irrespective of social or cultural differences. They comply with the principle of equal approach and equal opportunities. They refuse any form of sexual harassment."*<br><br>Due to limited scope of this document, only the principles of career development and employment policy of the LRI's hosting institution, Institute of Physics of the CAS, are described below. Other CERN-CZ institutions apply similar policies, see e.g. https://cuni.cz/UK-8762.html for Charles University.<br><br>FZU is aware of the importance of equal opportunities to the career development for its employees. Systematic care and recruitment of new employees is an essential factor in ensuring quality results across the institution. Therefore, in 2017, FZU applied for the certificate *HR Excellence in Research Award,* which was granted by European Commission in April 2019.<br><br>FZU is currently striving to implement the European Charter for Researchers and The Code of Conduct for the Recruitment of Researchers. The Charter & Conduct constitutes a framework for researchers, employers and funders and invites them to create and participate in a responsible professional working environment. The Charter & Conduct recognizes that researchers during their career fulfill multiple roles: as scientists, supervisors, teachers, managers, administrators, and science communicators. Emphasis is placed on continuous professional development in all areas related to these roles through specialised trainings including - apart from science related |

activities such as conferences and workshops -, also trainings in soft-skills, grant application and management skills through seminars and webinars, and also, for instance, training on internal processes through e-learning modules. Among other objectives of the project are internationalisation, including the assurance of equal access to information through a bilingual environment, and fair, non-discriminatory and objective recruitment process.

In 2019, FZU decided as well to strengthen knowledge of its employees in areas related to the topic of gender. There will be a campaign as well as training related to unconscious bias and gender sensitive communication.

CERN is a shining example of multinational cooperation in science and pursues its own policy of promoting diversity, which is crucial for such large international organisation. The Diversity Policy covers categories such as nationality/culture, profession, age/generation and gender, as well individual differences such as ethnic origin, sexual orientation, belief, disability, or opinions provided that they are consistent with the organization's values. The full document on Diversity Policy at CERN is available at diversity-and-inclusion.web.cern.ch. This policy applies not only to CERN employees, but also to all CERN users visiting CERN.

Equal opportunities applied by the CERN-CZ institutions do not necessarily lead to a proportional representation, which is strongly influenced by other sociological and historical factors. The gender composition of the FZU team copies the gender composition in technical and natural sciences with all known ailments. At the master and bachelor level, 28% of the LRI CERN-CZ employees are female students. Their share decreases to 20% in the case of doctoral studies, and further down to 6% for researchers with Ph.D, where the high proportion of men scientists is given mainly historically. An example of the LRI's active approach is the repeated action *"Become a Female Scientist Day"* at CTU, see the following section of the report.

III. Describe the outreach activities, advertising and promotion actions taken, steps towards better visibility of the LRI at a national and international level.

Excellent results marking the whole CERN history, its ambitious research programme, development and use of new technologies and perspectives for individual self-realization within the multi-coloured scientific environment show science in the best light. Scientists collaborating within LRI present all these merits in outreach events oriented towards students, teachers and the wide public.

Most of the outreach activities are periodic and their main aim is to saturate the high school population with information about CERN and generally about particle physics as one example of modern physics. Such activity are the International Masterclasses - Hands on particle physics – one day workshops organized by the Universities participating in LRI in collaboration with schools. The workshop consists of lectures, a "game with particle data analysis" and a videoconference with teams from other countries. This activity is coordinated by IPPOG (International Particle Physics Outreach Group), about 5 workshops every year in the CR target about 100-200 students.

Clearly periodical are the Open Days at institutions of LRI and other similar events (A week of science at the FNSPE at CTU, One day with physics at the FMF CU, …) also enhancing the visibility of LRI. One specific event is worth of notice: FNSPE at CRU organizes a special workshop for girls

to stimulate their engagement in science, see https://www.fjfi.cvut.cz/cz/media-a-verejnost/akce/vedkyne.

We devote significant attention to teachers, both students and teachers already in service, as we consider some knowledge of the microworld and particle physics to be a standard part of the education at the high school. We organize a short excursions to CERN filled with visits to experiments guided by Czech physicists (Excursions in years 2017, 18, 19 with 39 participants). A natural consequence of teacher's knowledge of CERN are school trips to CERN. We offer some assistance to organize them, but this activity becomes the business for the travel agencies.

A wide variety of activities is focused on the general public: public lectures within the framework of the Science Night, Science Café, Science to Go, Physics Thursdays at FEE CTU, University of Third Age at FMF CU …)

Some events step out from the variety of periodical ones. This was the CERN travelling exhibitions, which the local organizers won for the south bohemian capital České Budějovice. It attracted under the label Accelerating Science more than 22 thousands visitors in the period September 2016 – January 2017. Scientists from LRI offered assistance during the preparations of the exhibitions, helped with preparation of guides and held several lectures in the accompanying programme. Another singular event was the visit of the Director General of CERN Fabiola Gianotti in March 2017 and of the CERN Council Chairwoman Ursula Bassler in May 2019 when we took care of seminars and the media reflection of the visit.

The relations with media is positively influenced by our long-term cooperation and scientists from the LRI are invited to present opinions on questions relating to CERN. "Czech Media Day at CERN" in 2019 served to further improvement of this collaboration.

Another singular event has been the selection of 24 students and 3 teachers to participate in two-week CERN High School Students Internship Programme in May/June 2018. Since we could select only 24 participants of 238 interested students, we organized a week of lectures, visits to institutes of LRI and workshops in Prague in September 2018.

Following good examples from other countries, e.g. UK, we tried to address the general public at occasion when plenty of people concentrate at one place – at the music festival. We have made some experience with the limited offer of lectures at Colours of Ostrava 2018 and for the year 2019 we arranged a rich programme of lectures, workshops, shows, small experiments and virtual reality trips to CERN experiments. Several colleagues from CERN and UK helped us with the organization. The particle physics programme on the "Big Bang Stage" has been well visible part of the festival and attended by more than 4 thousands of visitors with very kind response.

We also organized several events to promote the career opportunities at CERN in other professions than physics, in Prague and in other regions of ČR.

The feedback from all events offers signals that the Czech public is proud not only of Czech hockey or tennis players but also of Czech scientists and of the fact that they contribute to current top science.

A natural part of all these activities is their international dimension; we also report on them in international bodies like Teacher and Student Forum and IPPOG.

## PART V. - CONCLUSION

| Final Assessment (Summary) |
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| Summarize conclusions of the project described in more details above. Describe the course of the realization, summarize the objectives achieved, the degree of expectations being met, assess efficiency of utilization of the funding and mention the targets that are yet to be achieved. |
| The LRI CERN-CZ organizes and supports the participation of universities and research institutions in the international laboratory CERN in Geneva. With the world's largest accelerator, the Large Hadron Collider (LHC), CERN plays a worldwide leading role in research of elementary particle physics and behavior of matter at extremely high energies. The goal of research at CERN is to broaden our knowledge of the basic laws governing matter behavior, including the principles under which our universe evolves.<br><br>CERN operates and hosts a number of unique accelerators and experiments. The best known and most important one is the LHC, fully operational since late 2009, fifteen years after project approval. The most significant LHC result so far is the discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments. During its operation, the LHC delivered several tens of inverse femtobarns ($fb^{-1}$) of proton-proton collisions at center-of-mass energy of 7 and 8 TeV and 150 $fb^{-1}$ at 13 TeV, which is the highest proton-proton collision energy achieved in the earth laboratory. Higher LHC collision energy and higher luminosity allow more detailed research of the Higgs boson properties and expand the LHC discovery potential for searches for new particles and new phenomena in particle physics and ultra-relativistic nuclear physics. This was the main scientific programme of the LHC experiments in the years 2016-2019, and this defined as well the main scientific goals of the LRI CERN-CZ in the reported period.<br><br>The LHC High Luminosity Upgrade (HL-LHC) is planned for the next long LHC shutdown currently scheduled for 2025-2027. In connection with HL-LHC, it is also necessary to upgrade the LHC experiments in order to be able to operate them in new harsh conditions of more intensive proton beams. Besides the participation in the operation of the experiments, the preparation for the HL-LHC upgrade of the ATLAS and ALICE experiments was the main activity of CERN-CZ in 2016-2019.<br><br>The aim of CERN-CZ is to support the development, construction, maintenance and operation of scientific facilities in CERN experiments with Czech participation. This includes the local infrastructure and laboratories in the CR, which are necessary for the research, development and production of these detectors, and computing tools for large scale data processing. The LRI is developing new technologies for particle detectors including their applications, especially in the field of calorimetry and semiconductor tracking detectors. The LRI's technical scope covers such areas as: design and construction of detectors; development of radiation-hard semiconductor detectors and electronics; cooling; cryogenics; vacuum technology; electronic and mechanical design; and large scale data processing.<br><br>The portfolio of services includes: operation and maintenance of detectors, in particular those that have been built partially in CR; upgrade and construction of new detectors; research and development of new technologies and detectors for future upgrades and new projects; operation |

of a computer center serving as a national Tier2 center in the hierarchy of CERN computer network; coordination of projects at CERN with CZ participation in cooperation with the "*Committee for Collaboration of the CR with CERN"*; representation and exercise of our country's rights in the governing and advisory bodies of CERN and individual experiments.

Unique scientific experimental facilities built with the contribution from the CZ institutions, form the core of LRI. Participation in their operation, maintenance and upgrades is a necessary condition enabling CZ scientists to have free access to unique data collected by these devices. This is the core benefit of CERN-CZ for the CZ user community. Scientists from CZ research institutions can thus contribute adequately to the excellent world-class results in the field of particle and nuclear physics produced by the experiments at CERN.

In total, 258 users from CZ institutes were registered at CERN in 2018. This represents 3.5% of CERN users from all CERN member states. This large fraction (the CR membership fees represent about 1% of CERN budget) documents that Czech particle physics community uses well the opportunities offered by the membership of the CR at CERN and that the community uses the CERN-CZ services extensively.

The facilities operated with the contribution from the LRI CERN-CZ are used extensively as well by the wide international scientific community. In the years 2016-2019 the experiments supported by CERN-CZ published more than 630 papers with fundamental results in the field of elementary particle physics and nuclear physics. Only the number of authors in the two experiments with the largest CZ participation, experiments ATLAS and ALICE, reaches almost 6000.

The activities of LRI CERN-CZ connected with the operation of scientific facilities, upgrades, design and construction of new detectors, and the development of new technologies for future particle detectors induced the LRI's own scientific results. The LRI's researcher published 58 articles in these categories.

The main objective of the LRI is to meet the CERN-CZ institutional commitments to the CERN experiments, whether financial, operational or constructional nature. The LHC experiments present the achieved results twice a year at the LHC RRB, including an overview of contributions for each national funding agency. The MEYS has in the LHC RRB its own delegate, which controls the achieved LRI's results and fulfilling the obligations of the CERN-CZ institutions towards the CERN experiments. We note that the international commitments of the CERN-CZ institutions have been met for the whole duration of the project in 2016-2019. In total, CERN-CZ contributed in form of membership fees 49.6 mil. CZK to the operation and maintenance of CERN experiments. In addition, the LHC experiments annually record the fulfilment of our manpower obligations to the operation, maintenance and detector upgrades at the level of 25 FTE. The local Tier-2 Computing Center enabled us to meet our WLCG pledges towards WLCG the ALICE and ATLAS experiments, which amounted to 30 000 HS06 and 3 400 TB of disk space in 2019. In 2016-2019, CERN-CZ also contributed 90.6 mil. CZK to the CORE costs of CERN experiment upgrades. This represents about 50% of the CERN-CZ institutional CORE costs commitments in current signed MoUs for construction.

In view of meeting the main objectives of the LRI CERN-CZ, we evaluate the utilization of the funding as efficient. The funding was used in connection with the fulfilment of the international CERN-CZ institutional commitments to the LHC experiments and other projects. Membership fees

were used to cover our financial obligations, whether of operational character or in construction for detector upgrades. Of the operational costs, the travel expenses constituted the major part, again linked to the fulfilment of the CERN-CZ operational commitments towards CERN experiments. This was also reflected in the personnel costs.

The CERN-CZ Advisory Board regularly oversees and comments on the effectiveness of the use of financial support as well. The Board also considers the use of funds to be appropriate, see the minutes of the last three Advisory Board meetings appended to the report. The Board also evaluates the level of scientific and operational activities of the LRI, expresses itself and makes recommendations on newly planned activities and on the long-term strategic infrastructure plans. Also in these matters, the Board evaluates the LRI CERN-CZ positively.

The LRI CERN-CZ is facing a challenging task of a longer-term nature, which concerns the upgrades of LHC experiments in connection with the LHC High Luminosity upgrade. The new detectors must be ready for installation in the next long LHC shutdown LS3 scheduled for 2025-2027. In this context, it is important that the funding of LRI CERN-CZ is secured under the Large Research Infrastructures programme also in the following period 2020-2022. It will enable us to fulfil our international commitments signed by the MEYS for HL-LHC upgrades of the ATLAS and ALICE experiments.

LHC experiments are a long-term project. The operation of the LHC is planned at least until 2036. During that time, the large LHC experiments, supported by CERN-CZ, will be in operation as well. Therefore, we plan to apply for funds for the operation of CERN-CZ under the Large Research Infrastructures programme also in the next call for the period 2023-2029.

CERN has the ambition to maintain its world leadership in experimental particle physics also after final LHC shutdown. CERN has prepared several designs options for the future accelerator, be it the linear electron and positron collider CLIC or the new generation of circular collider FCC. It has yet to be decided, which path to take. The Czech research institutions have a constant interest in participating on the world-leading CERN research programme. We will continue to develop the capabilities of the LRI CERN-CZ, so that it can continue to play a leading role in the organization of the Czech particle physics community and further develop close cooperation of Czech research institutions with partners in Europe and around the world on the prestigious research at CERN.

| **Appendices** |
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| **Mandatory:** Table of the real financial costs of the LRI over the entire period<br>**Optional:** Appendices relating to the realization of the LRI at discretion (max. 10 A4 pages). |

In Prague

Date: 30 January 2020

Signature of principal investigator: