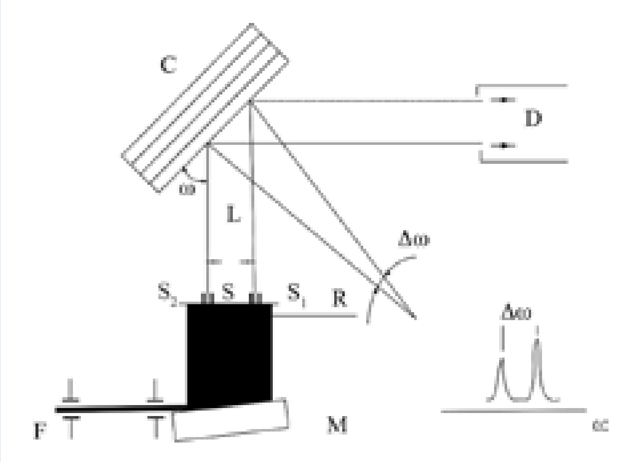

Fig.1. Laboratory setup for X-ray topography: F – X-ray source, M – monochromator crystal, S – slit, C – sample, D – detector. Double-slit mode provides measuring of the sample curvature.

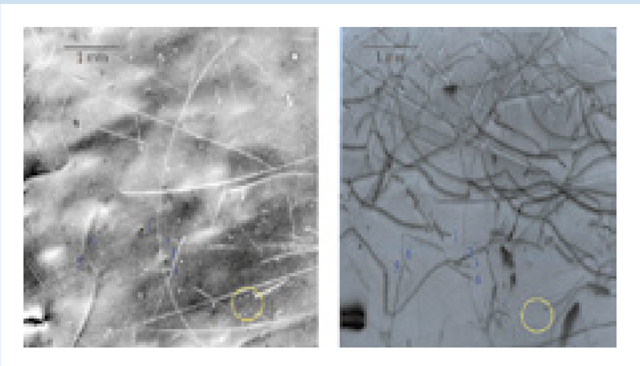

Fig. 2. Left: Laboratory topogram. Right: White-beam topogram. Identical dislocations are marked with blue numbers. Yellow circles also show the same defects.

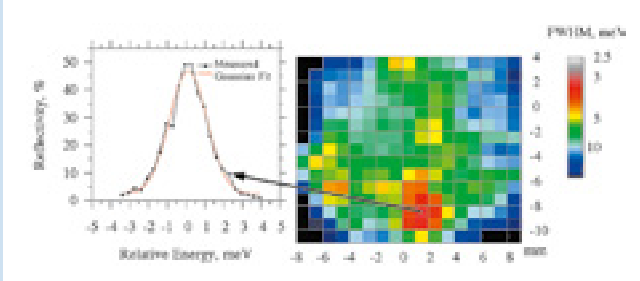

Fig. 3. Left: Backscattering spectral reflectivity measured at 24 keV at the best spot, and, left, map of the resolution function width of a sapphire grown by the Kyropoulos technique. Sapphire dimensions are in mm.

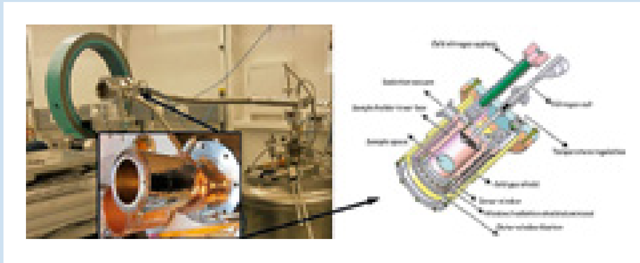

Fig. 4. Left: the housing for the sapphire, see inset, is mounted on a 2-circle Euler cradle and connected to a nitrogen cold gas generator. The sapphire is placed in the housing, see right, where the temperature is controlled with mK precision in order to carry nuclear resonance scattering measurements.

Fig. 5. New growth unit underconstruction.

In parallel to the sapphire characterization, an experimental setup for future nuclear inelastic scattering measurements using a temperature controlled sapphire as backscattering monochromator was constructed for the P01 beam line at Petra III, DESY, see Fig. 4.

Outlook

The immediate next steps in our project involve:

- systematic backscattering topography with meV resolution on the first batch of sapphires. These measurements will be carried out in February 2014 at the beam line ID18 of the European Synchrotron Radiation Facility.
- first tests of the backscattering monochromator at the P01 station of Petra III in January 2014.
- improvement of the growth technique for new batches of sapphires, which mainly involves a precise control of the requested very slow growth velocity that is required, see Fig. 5.

Acknowledgments

A. Danilewskii, U. Freiburg, is acknowledged for assistance during the white-beam topography measurement and evaluation. The ANKA, Petra III, and ESRF synchrotron radiation facilities are acknowledged for provision of beam time at TOPO-TOMO, P01 and ID18, respectively.

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STRUCTURE OF MATTER

The KArlsruhe TRItium Neutrino (KATRIN) experiment. Image by KARTIN/KIT

HRJRG-002

PHYSICS ANALYSIS AND CALORIMETRY AT THE TERASCALE

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The Helmholtz Russia Joint Research Group HRJRG-002 was approved in September 2007 to promote the scientific cooperation within particle physics and to provide attractive research conditions for young scientists. The program started on the 1st of November 2007 and ended on the 31st of October 2011. On average the group consisted of 20 members from DESY and the three Russian Institutes.

Goals and achievements of the group

The Helmholtz Russia Joint Research Group HRJRG-002 continued the long-lived and very fruitful cooperation between DESY and Russian Institutes beyond the common efforts for experiments at the electron-proton collider HERA at DESY, physics and detector R&D towards new activities at the proton-proton collider LHC at CERN in Geneva and for a future electron-positron linear collider (LC). Within the project excellent young scientists and students were supported and opened the possibility for a future career. All participating young PhD students achieved an attractive position in international recognized institutes. With the sound basis originating from the HRJRG the contributing PIs and group leaders were able to accomplish further career steps, for example becoming deputy spokesperson of the international CMS Collaboration counting ~4.300 members.

The combination of physics and detector activities pursued in this Joint Research Group made the project extraordinary and exceptional. The basis of the project was provided by the profound experience in detector operation and physics analysis collected at HERA. The gained knowledge flowed directly into an imminent project at LHC and provided input to the projects for the future linear collider LC. For this healthy project future prospects were opened by closely relating physics, experiment and the development of novel technologies for the next generation of colliders.

HERA & Phenomenology:
The results of HERA on the structure of the proton, the underlying event, multi-parton interactions and dependencies of several QCD processes provide crucial input for discoveries as for example the Higgs-boson, for searches for new physics phenomena as well as precision studies at the LHC to achieve sufficient accuracy and significance. The understanding of the HERA results with their consequences for the LHC needed and still do need a strong effort in phenomenology. The studies for the physics analyses, requiring significant computing, were performed at the Tier 2 centers in Russia and at DESY as well as at the National Analysis Facility at DESY.

The analysis of HERA data progressed with a new ansatz for a fit of the proton parton density functions. These new, so-called un-integrated, parton density functions are now regularly employed for simulations of physics processes at the LHC. The novel CMS data have been compared with predictions of the production of forward jets using these parton densities and open now the possibility to determine the parton densities with much improved precision.

Phenomenological calculations and studies have been performed for various physics processes at HERA, the Tevatron and the LHC, for example the production of prompt photons and W- and Z-bosons. These processes are most important standard candles in particle physics and are employed to validate the detector performance and calibration and to prepare the basis for the discoveries. The strong activity within phenomenology is proven by the impressively large number of publications with the results produced during the time of this HRJRG-002.

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CASTOR & LHC:
The correct extrapolation of HERA results into the kinematic regime of the LHC needs input of initial data with a special hadron calorimeter in the forward region. Members of the project participated in the construction and operation of this calorimeter, named CASTOR, cultivated skills obtained at HERA and developed further knowledge in detector operation.

The efforts for the forward calorimeter in the CMS Experiment at LHC were pretty exciting and challenging. Only this Helmholtz Russia Joint Research Group enabled the participation of DESY, MSU and ITEP in this project. The expertise flowing with these group members into the project was well appreciated by the CMS Collaboration, expedited the project considerably and in the end made it possible to be ready just in time albeit its start at a very late stage. First physics measurements of the energy flow in this novel kinematic regime as well as calibration and performance measurements with test beams at CERN have been published. During the time of the HRJRG-002 a new synergy with cosmic ray shower physics within the Helmholtz Young Investigator Group VH-NG-733 at KIT has been developed and bears excellent fruits.

HCAL & LC:
One mainstream activity for a detector for a future linear collider involving both DESY and the participating Russian institutes is the development of a hadronic calorimeter. A novel technology was invented in Russia for its readout based on solid state photo-sensors, the so-called SiPM. It is mandatory to strongly pursue its optimization to keep the leading position in this successful development. Beside this novel technology new reconstruction algorithms for hadronic energy deposition were developed and are still optimized employing the test beam data taken in different campaigns at CERN and FNAL.

Following the success of the first calorimeter prototype based on SiPMs, which was built by DESY and the Russian partners ITEP and MEPHI, the emphasis in the HRJRG-002 was on consolidating the technology, especially optimizing the layout of the scintillator tile read out, and exploiting the data collected at CERN and Fermilab test beams.

As a result, the calorimeter performance and simulation were validated, and a detector integration concept was developed which represents a competitive option for a linear collider hadron calorimeter. It is thanks to this effort that the particle flow concept is now considered as being experimentally and technologically established. A proof of the successful work for the R&D is the fact, that also the experiments at LHC took note and employ the technologies for their upgrades. For example in the CMS experiment the HCAL will be improved by changing the photon-detectors into SiPMs, the first part is already installed. For the future upgrade at even higher luminosities after ~2.022 calorimeters enabling the particle flow ansatz are the presently favoured option.

Conclusion

In summary the activities of the group were centered around the development of experiments in high energy physics from HERA towards the LHC and the LC. The performed HRJRG-002 was tailored to allow efficient participation in this programme by selecting a few important key topics where crucial expertise of participating Helmholtz and Russian institutes were brought in and further developed. Conducting the activities of the HRJRG as originally proposed strengthened the role of the participating Russian institutes and DESY in particle physics. The acquired experience provides the basis for a sustained, long-term participation in fore-front experiments of particle physics.

Acknowledgement

The members of the HRJRG-002 are very grateful to the Helmholtz Association and the Russian Foundation for Basic Research for providing such a successful funding support to intensify German-Russian collaborations and to foster excellent young scientists.

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- Deutsches Elektronen-Synchroton. DESY, Hamburg
- Institute for Theoretical and Experimental Physics, ITEP, Moscow
- Moscow State University, MSU, Moscow
- Moscow Engineering Physics Institute, MEPHI, Moscow

Group Members of the HRJRG-002:

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- Principle Investigator (Russia): Dr. Roman Mizuk (ITEP)
- Group Leaders: Dr. Felix Sefkow (DESY), Prof. Dr. Michael Danilov (ITEP), Dr. Michael Merkin (MSU), Prof. Dr. Boris Dolgoshein (MEPHI)
- 1 Key Researcher at DESY, 1 Key Researcher at ITEP
- 2 Post Doctoral Fellows at DESY, 2 Post Doctoral Fellows at MSU
- 3 Graduate Students at DESY, 3 at ITEP, 1 graduate student at MEPHI and 1 at MSU

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HRJRG-016

MAGNETIC NANOPARTICLES FOR BRAIN CANCER TREATMENT

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Cancer remains one of the most widespread diseases and leading cause of death worldwide, despite a certain progress in diagnosis and treatment methods in recent years. During last decade researchers have been investigating the applications of colloidal particles (or nanoparticles) that could act as delivery systems for targeted cancer drugs. The nanoparticles with radii between 1–10 nm provides large specific surface for functionalization (e.g. chemically active substances interacting with cancer cells). Along with it, if the magnetic nanoparticles are used, then, their transport and concentration in a given place can be additionally controlled by an external magnetic field, thus increasing the efficiency of the treatment, and, avoiding the spread of the nanoparticles in healthy tissues in the organism. Moreover, new possibilities for employing magnetic properties of the particles in medical diagnostics (magnetic resonance tomography) and therapy (magnetic hyperthermia) of cancer tumors appear.

The work of our Helmholtz-RFBR JRG (2007–2010) dealt with the study of magnetic nanoparticles with respect to their use in the treatment of brain cancer (glioblastoma). Biomedical applications require that magnetic nanoparticles are to be placed in liquid conditions. The corresponding systems are known as magnetic fluids (or ferrofluids). For colloidal stabilization of magnetic fluids, the particles are coated with special shells of surfactants or polymers. The choice of the ferrofluids with the double sterical stabilization of nanomagnetite by short mono-carboxylic acids (lauric and myristic acids) as a source of magnetic nanoparticles for brain cancer therapy in humans was justified. The structure research and development of the synthesis was resulted in record concentrations of magnetite in aqueous ferrofluids (up to 10 vol. %), which maintain their stability well in biological media. The presence of separate (non-aggregated) particles was shown for these systems. As a consequence, during in-vitro experiments a good penetration capability of magnetite nanoparticles with respect to cancer cells of glioblastoma has been revealed. The distribution of absorbed magnetite inside the cells was studied, which showed that nanoparticles are preferably adsorbed to karyons. It was proved that magnetic nanoparticles manifest low cyto-toxicity with respect to health brain cells (astrocytes) and moderate cyto-toxicity with respect to glioblastoma cells. With the help of a specialized magnetic unit the effect of an external magnetic field on the migration properties of the cells with incorporated magnetic nanoparticles in a physiological medium was studied. It was observed that the incorporated nanoparticles slow down the migration (increase in the tumor effective area) in the absence of the external magnetic field. When a static gradient magnetic field (strength of up to 170 mT, gradient of about 40 mT/cm) is on, a preferable migration towards the field increase takes place. A part of the cells migrating in this direction is at the level of 80–85%. The possibility for using gradient magnetic fields to control the cell migration in the case of glioblastoma with incorporated magnetic nanoparticles was concluded.

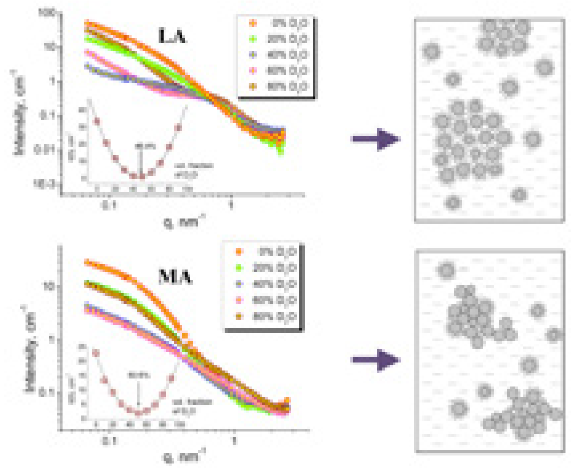

Figure 1. SANS contrast variation for 1% biocompatible aqueous magnetic fluids with magnetite coated by double layer of lauric (LA) or myristic (MA) acids. Changes in the scattering curves are followed when varying the content of heavy water (D2O) in the solvent. In insets the effective match points are found from the change in the forward scattering intensity. The revealed aggregation structures in the studied magnetic fluids are schematically shown to the right.

Figure 2. Participants of BIOFC Workshop, HZG, January. 2010

From the viewpoint of biomedicine, first of all, magnetic fluids should be considered as media for synthesis, storing and functionalization of magnetic nanoparticles. At the moment, there are several ways to stabilize water-based ferrofluids, but what concerns the biological media it is not possible to prevent aggregation completely. In biomedical context the formation of aggregates has side effects relating to the difficult elimination of nanoparticles from organisms, the possible appearance of blood clots, as well as the reduce in the therapeutic efficiency. Thus, the knowledge of aggregation regimes in magnetic fluids is a key point for their development in biomedical applications. In this connection, the important goal is a reliable diagnostics of aggregation and determination of the aggregation regimes and their control in biocompatible magnetic fluids.

For this purpose we developed the method of small-angle neutron scattering (SANS), which is quite sensitive to the aggregation processes in nanosystems. SANS is actively applied in structure research of magnetic fluids. The wide possibilities of the contrast variation (hydrogen/deuterium isotopic substitution) in neutron experiments allow us to 'look' inside the aggregates. Taking into account the complexity of magnetic fluids (which are mostly polydisperse), reasonable tasks for SANS in this case are to find out the type of aggregates formed in them under different conditions, conclude about their inner nuclear, as well as magnetic structures, and obtain information about interaction between their different components.

Different aggregate classes depending on the stabilization mechanism (steric, electrostatic and steric/electrostatic stabilization) of magnetic particles (magnetite) in physiological conditions were studied. In Fig. 1 example of the SANS contrast variation application is given for water-based magnetic fluids used as a source of magnetic nanoparticles in the therapy of the brain cancer glioblastoma. These fluids are characterized by record achievable concentrations of magnetic material (up to 10 vol. %) with keeping high stability. The systems were synthesized basing on the coating of nanomagnetite with a double layer of fatty mono-carboxylic acids with short alkene chains, namely lauric (C12) and myristic (C14) acids. Despite the high concentration and long time stability, SANS shows the presence of aggregates in the systems. The contrast variation was achieved by diluting the initial samples to one concentration with different mixtures of heavy and light water. The found effective match points (see insets to Fig. 1) are shifted and show a difference in the composition of the aggregates. Schematic views of the fluid structures in Fig. 1 illustrate the main important conclusion of the analysis: there is a different rate in the surfactant coating of the particles in the aggregates, which is consistent with the longer chain of myrstic acid. Among the studied systems in this way are water-based magnetic fluids with substitution of sodium oleate as surfactant by biocompatible polymer polyethyleneglycol at the magnetite surface, which aims at the increase in the life time of magnetic nanoparticles in living organisms by reducing the response of their immune systems. It was revealed that quite large amounts of polymer in the fluid structure results in a decrease in the aggregation stability, thus requiring that an optimal polymer content to be chosen.

As a result of the project, the Workshop on "Structural aspects of biocompatible ferrocolloids: stabilization, properties control and application" (BIOFC) was held in Geesthacht on January 28–29, 2010 (Fig. 2). It gathered together not only the participants of the Group but a number of researchers on closed topics from various centers of Europe and Russia. It opened up a tradition of holding BIOFC Workshops on a regular basis and was followed by the meetings in Dubna (Russia) on August 19–21, 2011, and Kosice (Slovakia) on August 25–28, 2013.

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HRJRG-106

DEVELOPMENT OF A HIGH ENERGY ELECTRON COOLER FOR HADRON PHYSICS EXPERIMENTS AT COSY AND HESR

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Precision ion beams are the ultimate tool for gaining new insights into hadron physics in the multi-GeV range. For example, experiments on hadron-induced reactions close to the threshold energy require ion beams with the lowest possible transverse and longitudinal phase space. COSY was successful in these areas with its electron cooling in the low energy range and complementary stochastic cooling in the high energy range. For future experiments, however, decisive limitations of existing experimental possibilities will become clear. Investigations into rare reactions will require a significant increase in luminosity. This can only be realized with other target techniques, for example the use of pellet targets. Such high-density targets consist of small micro-spheres (pellets) of frozen hydrogen (diameter 20–40 micrometers), and allow COSY's luminosity for internal experiments to be increased by more than one order of magnitude. However, the existing stochastic cooling is not in a position to compensate for the expected increased heating of the circulating beam using such targets, which means that the use of new targets would be counteracted by faster beam losses.

Because the completely new high-energy cooling system was developed for ion beams in the COSY ring. Together with the use of high-density targets, the method is intended to considerably increase the counting rate for studies on rare processes. Successfully implementing such a method is the only means of significantly reducing statistical errors in all experiments. At the same time, reducing the beam halo will considerably improve the data quality of future experiments.

The research and development projects connected with establishing this method of electron cooling and experience in using this type of cooled GeV proton beam represent a decisive milestone for the future utilization of cooled precision beams. Along with the expansion of the experimental possibilities at COSY, this step can also be taken as an essential preliminary stage in the implementation of high-energy electron cooling (8 MeV) at the HESR storage ring, at the future FAIR facility.

The idea of the electron cooler was proposed by the G.I.Budker in 1967 (Budker Institute of Nuclear Physics, Novosibirsk, Russia). The basis of the electron cooler process is the interaction of a "hot" ion beam circulated in the storage ring with a "cold" electron beam. The both beams move together along the special section of the storage ring. This method is widely used in the world for improving parameters of the ion beams. From 1988 the large number of the electron coolers was constructed in the different scientific centers LEAR, IUCF, TSR, CELSIUS, TARN-II, ESR, CRYRING, ASTRID, COSY, FNAL. The Budker Institute of Nuclear Physics produced 5 coolers for Germany (2), China (2) and LHC (1). Scientific collaboration with Germany on the electron cooling technology started from first experiments with cooling at Novosibirsk. It was visit young German science at BINP for study idea of cooling. Late the electron cooler was made at Darmstadt laboratory GSI by German specialist. This cooler is in the operation up to now and used for accumulation rare ions at synchrotron ESR. At 1996 additional new cooler was designed at BINP and installed at main synchrotron SIS-18. At 2013 first cooling experiment was started on new 2 MeV cooler at synchrotron COSY.

The feature of the electron cooler for COSY is combination of the wide energy range for operation and the high value of the maximum energy. After stopping FNAL electron cooler the COSY cooler becomes the highest energy electron cooler. The production of the electron cooler for COSY requires solving many physics and technical tasks: high-voltage accelerator column with longitudinal magnetic field, the optics of the electron beam in the longitudinal magnetic field in wide energy range, the high-vacuum technology, the transportation energy to devices located at high potential, the control system of large number devices in side high voltage tank and et al.

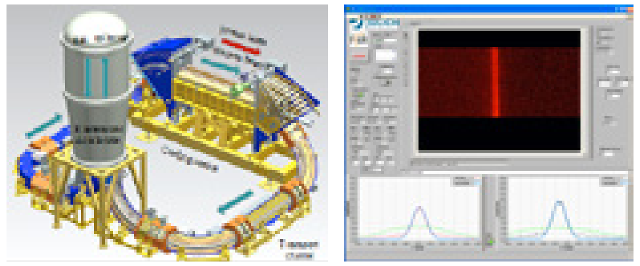

Figure 1: 3D design of 2 MeV COSY cooler. Shrinking of the proton beam profile at the electron cooling process.

Figure 2. Celebration of first cooling process in the COSY storage ring (Vsevolod Kamerdzhiev, Mao Lijun, Maxim Bryzgunov, Vladimir Reva, Dmitry Skorobogatov, Mikhail Kondaurov – stand from left to right, Juergen Dietrich, Vasily Parkhomchuk – sit from left to right).

The schematic design of the setup is shown in Fig. 1. The electron beam is accelerated by an electrostatic generator that consists of 33 individual sections connected in series. Each section has two high-voltage power supplies with maximum voltage 30 kV and current 1 mA. The electron beam is generated in electron gun immersed into the longitudinal magnetic field. After that the electron beam is accelerated, moves in the transport line to the cooling section where it will interact with protons of COSY storage ring. After interaction the electron beam returns to electrostatic generator where it is decelerated and absorbed in the collector.

During the COSY cooler project the follows milestone was completed. Manufacturing of the 2MeV cooler components was completed. The 2MeV electron cooler was assembled at BINP for electron beam commissioning. Required vacuum conditions in the cooler were achieved. High voltage and electron beam test was done. Electron gun perveance was measured and found in good agreement with computer simulations. Optical system of the scintillation profile monitor (SPM) at COSY was improved. Comparison measurements with SPM and IPM were performed, results are in good agreement. The 2MeV electron cooler was assembled and commissioned at FZJ in COSY storage ring (see Fig. 1.). Figure 2 shows the participants of the celebration of first cooling process in COSY ring.

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HRJRG-112

EXPERIMENTAL STUDY ON WARM DENSE MATTER BY INTENSE HEAVY ION BEAMS

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The Joint Research Group consisted of members from the Institute for Theoretical and Experimental Physics (ITEP, Moscow), Institute of Problems of Chemical Physics (IPCP, Chernogolovka), Joint Institute of High Temperatures (JIHT, Moscow), Technical University Darmstadt (TUD, Darmstadt) and GSI Helmholtzzentrum für Schwerionenforschung (GSI, Darmstadt).

The group aimed to study fundamental properties of high energy density (HED) matter using intese ion and proton beams available at two accelerator facilities – SIS-18 at GSI and TWAC at ITEP. Experimental investigations on the thermodynamic and transport properties of various materials in HED states were carried out. In particular, new experimental data has been obtained on thermophysical and transport properties such as heat capacity, thermal emission, optical reflectivity and electrical conductivity of refractory metals (tungsten and tantalum) during melting and in hot expanded liquid states as well as of other elements in the near and suprer-critical states, and spectroscopic studies on beam-induced light emission from dense gas targets relevant to the problem of transverse diagnostics of intense focused heavy ion beams have been performed. This data has been collected during a number of joint beam time experiments at GSI (over 700 hours of beam-on-target) as well as at ITEP.

HRJRG has developed, commissioned and applied sophisticated diagnostic instruments and methods for measuring basic physical parameters of warm dense matter (WDM) under the specific conditions of ion-beam heating. This includes fast radiation pyrometry with emissivity measurements, interferometric techniques for precision measurement of target velocity, volume and pressure, backlighting and schlieren methods using different photon sources for characterization of the hydrodynamic response of the on-beam heated matter and methods for transverse diagnostics of intense strongly focused heavy ion beams.

THe group has also designed and constructed a worldwide unique facility for high energy proton microscopy (HEPM) experiments- PRIOR (Proton Microscope for FAIR). HEPM is a novel technique in HEDP and WDM research for probing the interior of dense objects by mono-energetic beams of GeV-energy protons. HEPM has also a great relevance for biophysics, medicine and industrial applications. Two international workshops on HEPM have been organized by the group in Germany and in Russia.

The activities of HRJRG have secured the essential basis for the future HED physics experiments that are planned at the future Facility for Antiproton and Ion Beams (FAIR) in Darmstadt, Germany. Several PhD students and young researchers both from Russia and from Germany have been supported. Three PhD works have been completed in the frame of the project. The group has promoted frequent visits of young Russian researchers to GSI where they were gaining unique experience of joint scientific work at high international level.

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HRJRG-214

CONTROL OF NON-LINEAR PHASE SPACE DILUTION AND BEAM LOSS IN AN ENERGY RECOVERY LINAC: THE WAY TO SHORT HIGH INTENSITY AND LOW EMITTANCE ELECTRON BUNCHES

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The group uses synergies between laboratories of the Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia and institutes of Helmholtz Zentrum Berlin (HZB) für Materialien und Energie, working in the field of Energy Recovery Linacs (ERL). The research topics include

- Operational issues of the Novosibirsk ERL and Free Electron Laser (FEL), including design and diagnostics of the 4-turn ERL
- Operation of high brilliance electron sources
- Design of the accelerator for the Berlin Energy Recovery Linac Project (BERLinPro)
- Design of the future ERL-based synchrotron light sources: Multiturn Accelerator-Recuperator Source (MARS) and Femto-Science Factory (FSF)

In the following a short summary of results achieved during 2011–2014 is given.

Radio-Frequency electron sources at BINP and HZB

Assembling and commissioning of the NovoFEL radio-frequency (RF) gun test facility was finished. The nominal accelerating voltage 300 kV at RF cavity of this gun and average electron beam current 40 mA were obtained. The diagnostics beam-line was developed and assembled and the first experiments with electron beam have started.

Two prototypes of superconducting RF gun were commissioned at HZB [4,5,9,13,16]. The beam parameters were measured. To explain the obtained data numerical modeling of the electron emission process from the cathode surface and from the micropoints located in the vicinity of the cathode was carried out. It was shown that the main reason of the emittance dilution is the roughness of the cathode surface [15]. The processes of the dark current formation and micropoints heating were also investigated. Based on this research the new method of superconducting RF cavities processing was proposed. Beam stability in the SRF gun cavity was studied [2].

Cathode insert design for a Superconducting Radio Frequency (SRF) gun cavity

Future light sources based on the energy recovery linac (ERL) require high brightness high current electron sources. A source meeting these requirements is the superconducting radio-frequency (SRF) photoinjector under development at Helmholtz Zentrum Berlin. The gun consists of a normal-conducting photocathode with high quantum efficiency grown on a cathode plug embedded inside a SRF gun cavity. The photocathode must be thermally and electrically insulated from the SRF cavity. A special photocathode insert was designed and built [14] to allow transfer of plugs into the gun cavity. Another task of the cathode insert is to carry away the heat power induced by RF fields and the drive laser on the cathode. Liquid nitrogen is used for cooling.

In order to test different contact and holding methods for the cathode plug on the cathode insert the thermocontact experiment was set up. Temperature and cooling performance measurements at heat loads of up to 10 W of power at significant points in the system were performed. The heating power can be introduced into the system either by Kapton foil heater glued to the cathode plug or with a high average power laser. The setup is now under commissioning.

Dark current measurements in the SRF guns

ERL projects rely on effective beam collimation to avoid dark current and beam tails losses in the accelerator. Collimator design for the injector of BERLinPro was proposed. The dark current measurements were done for BERLinPro prototype guns [11].

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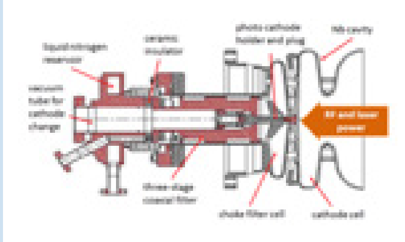
Figure 1. Normal conducting RF gun at BINP.



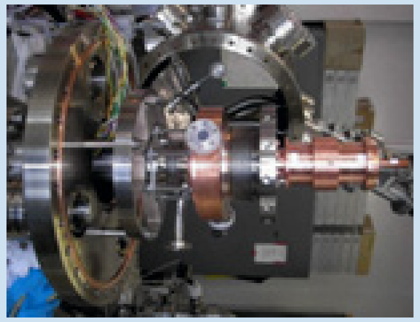


Figure 2. Insert design (above) and photo of the insert in the thermal test stand (below).

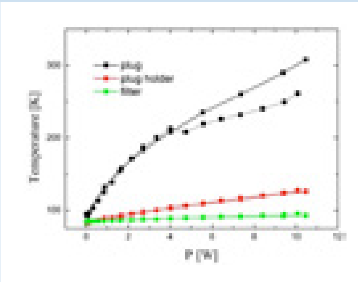


Figure 3. Results of temperature measure-ments of cathode plug with heater foil.

Magnetic optics design for short pulse ERL operation

Modelling and optimization of the optic for NovoFEL and BERLinPro with the focus on the short pulses was done. Beam dynamics simulations including space charge effects [3,7,10], coherent synchrotron radiation, and non-linear fields were carried out [6]. Beam parameters were measured at NovoFEL and compared with the simulation results. The lattice of the second order achromatic bend was calculated. For these calculations the measured magnetic field distribution was used. 5 mA average current in the 4-turn operation was achieved that is the world record for multi-turn ERLs. Based on the simulation and measurements results BERLinPro magnets design was done [6].

Design of future ERL-based synchrotron light sources

Feasibility studies of the 4-th generation SR source based on the multiturn ERL with separate tracks for accelerating and decelerating beam was done by both teams at Novosibirsk and Berlin. The MARS [8] and FSF [12] projects are both in the phase of conceptual design preparation. Essential parts of the design were done in the framework of the joint research group.

The project of the compact ERL based free electron laser for the ultraviolet region was considered by the teams [1].

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HRJRG-303

MEASUREMENTS OF GAMMA RAYS AND CHARGED COSMIC RAYS IN THE TUNKA-VALLEY IN SIBERIA BY INNOVATIVE NEW TECHNOLOGIES

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The measurement of the high-energy particles arriving at earth from the cosmos provides a crucial observational window to the most energetic and violent processes in the Universe like Supernova explosions, Gamma Ray Bursts, or Merging of Galaxies. To considerably improve the accuracy of these measurements, two new technologies are presently developed within the project in the Tunka Valley located 50 km off Lake Baikal in Siberia. These two techniques are: new generation wide-angle air Cherenkov detectors and recently developed radio antenna for measuring cosmic rays. Both detectors are deployed in the Tunka facility in Siberia and operate together with the established Tunka-133 air shower array. The development of these techniques extends the observational potential of high energy gamma ray and cosmic ray experiments and will allow to address the most intriguing problems of physics, including dark matter, quantum gravity and the evolution of our Galaxy.

Beyond its original objectives, this HRJRG already after its first year initiated a new quality of german-russian collaboration in astroparticle physics: the HRJRG-driven prototype designs triggered the TAIGA-project at Tunka, that is based on a successfull Russian MEGA-Research Grant, awarded to a group headed by a leading scientist from a german Max-Planck-Institute.

Introduction

Gamma-ray astronomy is a rapidly developing area with many impressive results and a huge impact to fundamental physics. A number of high-performance instruments including satellites and Cherenkov Telescopes are operating today. While about 100 of sources are observed at energy higher than 1 TeV, no single photon has been detected above 100 TeV. The latter energy region is of primary interest for both astrophysics and fundamental physics. Uncovering this new energy window will enable us to:

- identify the most energetic cosmic objects;
- test physical processes at energies not achievable in man-made laboratory experiments;
- study candidate particles for the mysterious dark-matter such as the axion-like particles;
- search for a decay of superheavy dark matter.

The goal of the project is to develop and test two new experimental techniques which will improve the sensitivity of cosmic-ray and gamma-ray observations: next-generation air-Cherenkov detectors and the radio technique. The Tunka facility in Siberia provides a world-wide unique environment for the deployment of these innovative detectors. It provides the required infrastructure and at the same time it is the location of the Tunka-133 array. The latter consists of state-of-art detectors which are used in the project as a well established reference for tests of the new detectors.

Tunka-HiSCORE – the next-generation air-Cherenkov detector

The question of the origin of cosmic rays remains unsolved, even after a century of observations. If cosmic rays are indeed accelerated up to 10^{17} eV inside our Galaxy, there must exits Galactic "pevatrons" which emit gamma-rays and neutrinos at energies around 100 TeV and up to few PeV. The main motivation for HiSCORE is the search for the origin of cosmic rays, and more specifically, the search for cosmic ray pevatrons in the gamma-ray regime. At the same time, HiSCORE will be a valuable cosmic ray detector. Furthermore, HiSCORE will also provide the possibility to address fundamental questions of particle physics using air-shower data, like a search for axions in the Galactic magnetic field and for superheavy dark matter, and a search for Lorentz invariance violation.

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Figure 1: A Tunka-HiSCORE Cherenkov detector station, one of nine stations operating since October, 2013 in Tunka. Design and construction was in close collaboration between russian and german groups.

Figure 2: R.Wischnewski mounting electronics components for the HiSCORE prototype station.

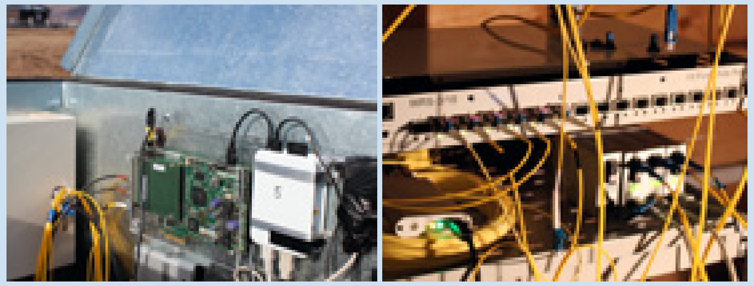

Figure 3: Nanosecond-TimingUnits (WhiteRabbit) installed in HiSCORE stations (upper) and in the counting room (lower).

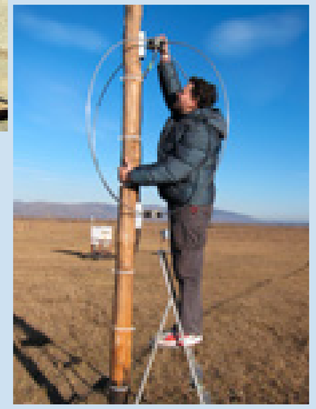

Figure 4: G. Rubtsov mounting antenna station, October 2012.

With HiSCORE, we are pursuing the concept of non-imaging air Cherenkov astronomy, based on the collection of Cherenkov photons from air showers on the observation level using wide-angle detector stations. The non-imaging technique allows to build a detector with a large field of view and to equip very large areas with a relatively small number of photosensors. In the case of HiSCORE as described here, only of the order of 200 sensors/km^2 are necessary. As opposed to that, a typical imaging air Cherenkov telescope array comes along with 10.000 data channels/km^2. Therefore, the non-imaging technique is well suited to detect ultra-high energy gamma-rays, for which huge detector areas are most important.

Design and construction of the wide-angle Cherenkov gamma-ray observatory Tunka-HiSCORE to study gamma-quanta fluxes from known galactic sources and unknown new sources is well advancing. The detector stations are placed at distances of 150 m from each other and are made of four photosensors (PMTs) with large area photocathodes (~20–30 cm in diameter), see fig. 1. The effective area of each PMT in the station is increased by four times by Winstone cones; this in turn decreases the energy threshold by a factor of 2. The observational solid angle is approximately 0.6 sr.

Within the project in 2012–2013 the first 0.1 km^2 area prototype array was build. This array consists of 9 optical stations with 4 PMTs each (see Fig.1), and is in routine operation since October 2013. The next development step is the installation of an 1 km^2 array and then its extension to 10 km^2.

For the Tunka-HiSCORE telescope, the biggest experimental challenge is the precision measurement of the light arrival times at all detector stations, distributed over many square-kilometers. A precision of 1 nanosecond (10^{-9} sec) is required for good angular resolution of gamma sources. For this purpose, typically a huge effort is undertaken by constructing application specific systems. The HRJRG has followed a less cost and labor intensive way – applying with minor modifications a state of art system, that has been developed at CERN for the usage at eg. LHC and is now in its test phase. This "White Rabbit" system (see fig. 3) is based on the well established ethernet-technology. In collaboration with a young team from Humboldt University Berlin (joining the HRJRG effort in 2012) a full scale prototype has been build and installed within a few months. After successful verification, White Rabbit is now at the heart of the 0.1 km^2 prototype array. This new technology can be applied also for other detector subsytems planned in the Tunka-array.

We note, that the first large-scale installation of WhiteRabbit in Tunka-HiSCORE triggered also another synergy: DESY is considering to apply this technique also in the large CTA-project.

Tunka-REX radio array

Since the measurements of cosmic rays have reached the theoretical limit for energies, the main challenge for the physics of ultra-high cosmic rays is to increase the statistics and the measurement quality near the Greisen-Zatsepin-Kuzmin energy spectrum cut-off. To obtain a sufficiently large data sample from a detector on the surface of the Earth, we need to build economically reasonable large-area detectors with a high duty cycle. The radio detection method could be one of the perspective techniques for future investigations of ultra-high energy cosmic rays. Radio emission from extensive air showers was theoretically predicted and first detected about 50 years ago. The radio detection techniques became popular in the last decade again, because standard detection methods have reached technological and economical limits Thus, a number of modern experiments aim at obtaining the main properties of extensive air showers, such as arrival direction, energy, shower maximum, and primary particle using the radio detection technique. These experiments proved that the radio emission can be detected from air showers with energies above 10^{17} eV, with an angular resolution for the arrival direction better than 1 degree. The open question is the precision of the reconstruction for primary energy and shower maximum. The current challenge is to reach a competitive precision with an economic radio array which can be scaled to very large areas.

The Tunka Radio Extension (Tunka-Rex) was deployed in the Tunka valley by this HRJRG. Tunka-Rex currently consists of 25 stations with a typical distance of 200 m, one next to each cluster center of Tunka-133. Each station consists of two crossed SALLA-type antennas to measure two components of the polarization. Tunka-REX is triggered externally by Tunka-133, and detects the radio emission of the same air showers. The combination of an air-Cherenkov and a radio detector provides a facility for hybrid measurements and cross-calibration between the two techniques. The main goal of Tunka-Rex is to determine the precision of the reconstruction of air-shower parameters using the radio detection technique, based on the cross-calibration with an air-Cherenkov detector. Data of both detectors are recorded by a shared data-acquisition system, and the radio antennas are triggered by the photomultiplier measurements.

Tunka-Rex started operation on 8 October 2012 (see Figure 3). Since then it operates within the Tunka-133 trigger, i.e. in dark moonless nights with good weather. As a result of the first year of operation, Tunka-Rex registered 131 events with a significant radio signal from extensive air showers with energies above 10^{17} eV in combination with the Tunka-133 air-Cherenkov array. This shows that the Tunka observatory is able to provide hybrid measurements which is the pre-requisite to perform a cross-calibration between the air-Cherenkov and the radio signal.

Conclusion

The project HRJRG-303 is an effort of young German and Russian researches under the guidance of experienced researchers in the field started in spring, 2012. A group from Humboldt University Berlin (Informatics) has joined thereafter. Within 2 years, about 25 presentations on 18 national and international conferences were given. Two major results have been achieved so far:

1. A prototype of the new generation wide-angle air Cherenkov detector Tunka-HiSCORE has been build and is in routine operation. With 0.1 km^2 instrumented detector area and 9 stations with 36 large area photosenors, the proof can be done that this technology allows to reach precision timing, a superior field of view and an extended energy range, compared to existing setups.
2. The Tunka-REX antenna array is operating since October 2012. The array registered 131 cosmic ray events for an effective measurement time of 392 hours.

The results will clarify the sensitivity and capability of the new detection methods and therefore might contribute to the design of large scale projects like the next generation cosmic ray experiment AugerNext and the high energy gamma-ray project Cherenkov Telescope Array (CTA).

As next steps we plan the deployment of 1 km^2 and 10 km^2 Tunka-HiSCORE arrays which will allow for physics results and will target the fundamental puzzles of physics, including dark-matter, quantum gravity and the origin of the cosmic rays. Moreover, the research may shed a light on the nature of the high energy neutrinos, recently discovered by IceCube detector.

With the specific aspect of this HRJRG group to execute the common research program at a Russian research facility, that had developed over the last 20 years, we are working successfully on optimal research, communication and organizational conditions and development of state of art technologies. HRJRG-303 activities already stimulated a successful application for a Russian MEGA-Research Grant, now linking in addition to Helmholtz also a Max-Planck Institute to the

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HRJRG-400

DEVELOPMENT OF A PHOTO CATHODE LASER SYSTEM FOR QUASI ELLIPSOIDAL BUNCHES AT A HIGH BRIGHTNESS PHOTO INJECTOR

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Introduction

A high brightness electron source is one of the key issues for successful operation of linac based Free-Electron Lasers (FELs) like the Free-electron LASer in Hamburg (FLASH), and the European X-ray Free-Electron Laser (European XFEL). The Self Amplified Spontaneous Emission (SASE) of the FEL process requires an extremely high space charge density of the radiating electron bunches implying high peak current, low energy spread and small transverse emittance of the electron beam. The latter property cannot be improved in a linac and thus the emittance has to be minimized already in the injector. The Photo Injector Test facility at DESY, Zeuthen site (PITZ), aims to produce electron bunches with extremely small transverse emittance. Cathode laser pulse shaping is one of the key issues for high brightness photo injector optimization. A flat-top temporal profile of the cylindrical pulses reduces significantly the transverse emittance of space charge dominated beams. As a next step towards further improvement in photo injector performance 3D pulse shaping is considered. An ellipsoid with uniform photon density is the goal of the studies in the frame of a Joint German-Russian Research Group, including the Institute of Applied Physics (Nizhny Novgorod), Joint Institute of Nuclear Research (Dubna) and the Photo Injector Test facility at DESY, Zeuthen site (PITZ). The major purpose of the project is the development of a laser system capable of producing 3D quasi ellipsoidal bunches and supporting a bunch train structure close to the European XFEL specifications. The laser pulse shaping is realized using the spatial light modulator technique. Laser pulse shape diagnostics based on a cross-correlator is under development as well. Experimental tests of the new laser system with electron beam production are planned at PITZ. First tests on the quasi ellipsoidal laser pulse shaping are ongoing now.

Beam Dynamics Simulations

3D shaping of photocathode laser pulses is considered as a next step for further optimization of high brightness photo injectors. Beam dynamics simulations have demonstrated a significant reduction of the transverse emittance of electron bunches produced by applying 3D ellipsoidal laser pulses to the RF photo gun. In order to illustrate the effect of 3D ellipsoidal pulses usage of the electron bunch properties simulated for such laser pulses were compared to results of simulations with cylindrical pulses with Gaussian and flattop temporal profiles. The European XFEL photo injector layout (1½-cell L-band RF gun and the first cryomodule with 8 superconducting TESLA cavities) was used as a benchmark for this comparison. The results of these simulations are shown in Fig. 1 for three above mentioned temporal pulse profiles. There is a clear advantage of the flattop laser pulse (which is currently the nominal pulse shape at PITZ) compared to the Gaussian temporal profile (which is a standard profile worldwide) in terms of projected (–40%), average slice emittance (–24%) and average slice brightness (+51%).

Further significant improvements on the electron beam brightness can be obtained by applying 3D ellipsoidal pulses of the cathode laser. So, the projected transverse emittance from the flattop pulse can be reduced by further ~32%, the average slice emittance by ~32%, the average beam brightness is by 77% higher. These advantages of 3D ellipsoid laser pulses motivate experimental studies on such a cathode laser system in order to provide headspace on emittance/brightness required from the electron sources for a successful operation of modern FEL facilities.

Experimental developments on 3D ellipsoid laser pulses

A laser system capable to produce quasi 3D ellipsoidal UV pulses is under development at the Institute of Applied Physics (Nizhny

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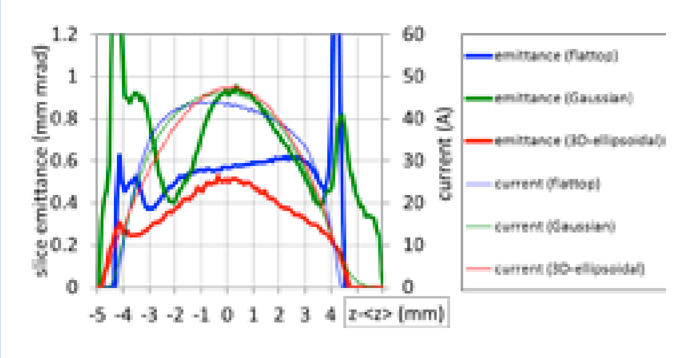


	Cath. Laser pulse profile		
Parameter	Flattop	Gaussian	3D ellipsoid
ε_{proj}, [mm mrad]	0.63	1.05	0.43
(ε_{slice}), [mm mrad]	0.55	0.72	0.40
(B_{slice}), [A ·(mm mrad)$^{-2}$]	135	90	240

Figure 1: Simulated properties of electron bunches in a photo injector for various temporal profiles of the cathode laser pulses applied: flattop, Gaussian and 3D ellipsoid. Left plot represents the normalized transverse slice emittance ε_{slice} distribution along the electron bunch (thick curves, left axis) and the corresponding beam current distributions I_{beam} (thin curves, right axis). The table represents the values of the normalized transverse projected emittance ε_{proj}, the normalized average slice emittance (ε_{slice}) and the average beam brightness $(B_{slice})=(I_{beam}/\varepsilon^2_{slice})$.

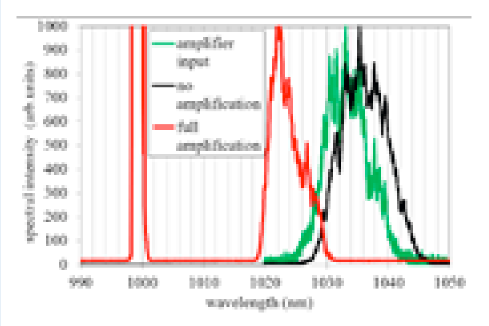
Novgorod, Russia) in collaboration with the Joint Institute of Nuclear Research (Dubna, Russia). PITZ at DESY (Zeuthen site, Germany) is the facility for experimental tests of this system with electron beam production. The laser system consists of a two-channel fiber laser, a diode pumped Yb:KGW disk amplifier, a 3D pulse shaper and frequency conversion crystals for second and fourth harmonics generation. A scanning cross-correlator system was developed and built to measure spatial and temporal distributions of the laser pulses.

The fiber laser oscillator generates 150 fs pulses at 45 MHz repetition rate. It includes a fiber pulse stretcher, a preamplifier and a system for pulse train (macropulse) formation. A piezoceramic cylinder inside the optical fiber coil of the oscillator is used for precise tuning of the pulse timing to the RF phase of the gun. The fiber laser output is splitted into two channels – working and diagnostics. Each channel is supplied with a powerful fiber amplifier. The spectra of both channels are centered at ~1.030 nm and have a width of 11 nm (FWHM). A typical spectrum measured at the fiber oscillator output is shown in Fig. 2a (green curve). The pulses from the working channel are amplified using a multipass Yb:KGW disk amplifier with a diode pump source LDM 2000-100, which was produced by Laserline GmbH. Due to the nonhomogeneous amplification spectrum the center wavelength is shifted to 1.035 nm. However, in the case of strong amplification the crystal absorption spectrum is being strongly modified and the center line is strongly shifted to 1.022 nm (Fig. 2a). The dependence of micropulse energy after the amplification on the pump intensity is shown in Fig. 2b.

The working channel is used for further amplification, 3D pulse formation and frequency conversion. The pulse shaper is realized on a scheme based on Spatial Light Modulators (SLMs). The principle scheme of the 3D pulse shaper is shown in Fig. 3. The pulse shaper is based on a zero dispersion optical compressor. It consists of two diffraction gratings, two single Kepler telescopes with cylindrical and spherical lenses and two liquid crystal based SLMs. The modulators are located at the focal plane of the telescope made of cylindrical lenses which images one diffraction grating onto the other in the meridian plane (plane of the sketch in Fig. 3a). There is no such imaging in the sagittal plane which implies corresponding diffraction. However, these effects are not substantial for laser beams of 8 mm diameter focused by a cylindrical lens with a 405 mm focus. A telescope with spherical lenses images one SLM onto the other. The first SLM manipulates the phase of the laser pulse. A half-wave plate is installed before the second SLM. This introduces a 45 degree rotation of the laser pulse polarization and therefore the second SLM becomes an amplitude manipulator. The laser pulse is passing through the pulse shaper twice (Fig. 3a). The first pass forms the laser profile in the meridian plane and time, the second pass after a 90 degree rotation is responsible for the pulse shaper formation in the sagittal plane and time.

The HES 6010 NIR SLM produced by Holoeye Photonics AG (Germany) is used for the pulse shaper tests. According to the technical certificate its reflection must not go below 60%. The measurements gave a value of 72% for horizontal polarization, required for the realized diffraction grating. But this value is a result of a rather long term averaging. At the ms time scale (Fig. 3b) the signal after the SLM acquires a strong noise. This unexpected SLM property complicates the pulse shaping significantly. Different solutions with this SLM (including cooling of the SLM screens and tests with thicker liquid crystal matrix) did not bring significant reduction of the noise. Currently another type of SLM (Hamamatsu X10468-03 LCOS-SLM) with better stability control is under consideration.

The diagnostics channel is used to measure the spatial and temporal characteristics of the pulses generated in the working channel. A high speed delay line is implemented in this channel in order to realize a high precision 3D pulse shape diagnostics realized in a scanning cross-correlator (SCC). A BBO crystal with 1 mm thickness is used for the nonlinear second harmonic generation from the non-collinear pulses overlap using varying time delays. Fig. 4a illustrates the working principles of the scanning cross-correlator. The major challenge for the SCC development was a high scanning speed determined by the macropusle duration (T=300 µs). A working laser pulse with t_m duration has to be scanned by a short diagnostic pulse of t_d length during the macropulse. Including margins to the working pulse duration implied a measurement window $t_w>t_m$ (Fig. 4a) within which the scanning has to be performed. The minimum time resolution of the SCC is determined by the number of pulses in a macropulse



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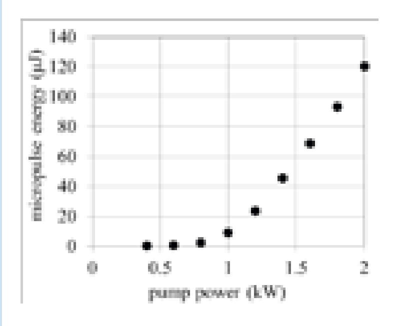
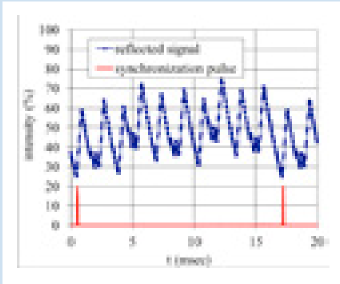


b.

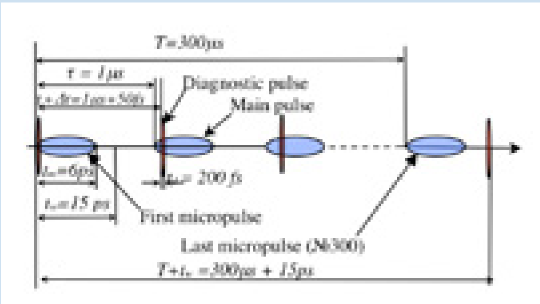
Figure 2: a) Spectra of the fundamental harmonics: fiber oscillator output (green curve) and measured w/o (black curve) and with full (red curve) amplification. b) Dependence of micropulse energy (fundamental harmonics) after the amplification on the pump intensity.

a.

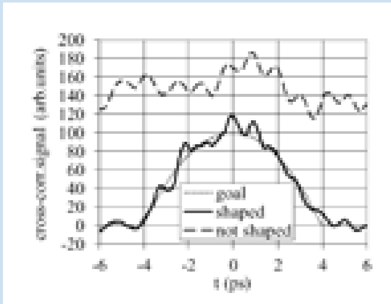


b.

Figure 3: a) Setup of the 3D pulse shaper: Diff. gr. – diffraction gratings, SLM – spatial light modulator, WP – half-wave plates, CL – cylindrical lens, FR – Faraday rotator, CW – calcite wedge, Rot. 90 degree – rotator of the laser beam by 90 degree. b) Time evolution of the SLM reflectivity. Synchronization pulses from the SLM are shown on top of the horizontal axis.



a.



b.

Figure 4: a) Time scheme of the scanning cross-correleator for 3D pulse diagnostics. b) Profiles of the measured cross-correlator function: upper dashed line – no pulse shaper applied, solid line corresponds to the amplitude mask applied to form the quasi ellipsoidal pulse and additionally a theoretical profile of the ellipsoidal pulse (dotted curve).

N=300. A time step of the scanning procedure is $\Delta t=t_w/N=50$ fs. This is an estimation of the lower limit of the time resolution under the assumption of an infinitely short diagnostic pulse.

A simplified 3D pulse shaper setup for quasi ellipsoidal pulse generation was tested using the scanning cross-correlator. Linear chirped laser pulses with 40 ps length and 11 nm bandwidth were used for preliminary experiments. Only the amplitude mask was applied to form the pulse shape. The measured profile of the fundamental harmonic pulse is shown in Fig. 4b. The possibility to utilize a pulse train with 1 MHz pulse repetition frequency and 300 µs macropulse length to characterize picosecond pulses was successfully demonstrated. A time resolution of ~200 fs was achieved for the measurement window of 50 ps. First experiments to generate quasi ellipsoidal laser pulses were performed.

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~~The first publication is also translated in English and published.~~

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TOPOLOGICAL SURFACE STATES UNDER THE INFLUENCE OF THE EXCHANGE INTERACTION

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Topological surface states are a fascinating research subject. They require strong spin-orbit interaction, are highly spin polarized, enjoy protection of their existence by time-reversal symmetry and have promising implications for electrical transport and spin transport. Magnetism, here in the form of the exchange interaction, breaks time-reversal symmetry and therefore should strongly interact with topological surface states.

We have demonstrated that this interaction is not as strong as expected. Instead, the combination of magnetic material and topological material can lead to a number of new physical phenomena in addition to band-gap opening at the Dirac point, e. g., the quantum anomalous Hall effect. Since apparently little is known about the strength and spacial range of the interaction of topological surface states and magnetic materials, our concerted study of this subject in various classes of materials:

1. magnetic surface impurities and films deposited on topological insulators,
2. magnetic material in the bulk forming a dilute topological insulator,
3. magnetic films on a topological metal,
4. graphene turned magnetic topological insulator by intercalation.

The methods of investigation are ARPES, spin-ARPES and spin-PEEM as well as XMCD and the project integrates essential expertise by chemists (Prof. L.V. Yashina group) and surface scientists (Prof. A.M. Shikin group) and brings along multiple research opportunities for young scientists from Berlin, Moscow, and St. Petersburg.

We studied the effect of Fe impurities deposited on the surface of the topological insulator Bi_2Se_3 and Bi_2Te_3 by means of core-level and angle-resolved photoelectron spectroscopy. The topological surface state reveals surface electron doping when the Fe is deposited at room temperature and hole doping with increased linearity when deposited at low temperature (8 K). We show that in both cases the surface state remains intact and gapless, in contradiction to current belief. The topological surface state of Bi_2Te_3 leads to high photoemisson intensity from its Dirac point. This allows us to investigate the effect of larger amounts of deposited Fe than previously achieved for Bi_2Se_3. The Dirac point is shown to stay intact up to at least a monolayer showing the robustness of the topological state towards disordered magnetic moments [1]. Our results suggest that the surface state can very well exist at functional interfaces with ferromagnets in future devices.

In collaboration with Institute of Solid State Chemisctry RAS (Prof. M. Kuznetsov) we studied the structure of Fe/Bi_2Te_3 interface from atomic level to submicron scale. At the atomic level interface reactions are observed. Adatoms relax strongly into the Bi_2Te_3 lattice and form chemical bonds both with Bi and to Te. Adatoms further react to substitute Bi, which is promoted by temperature. In addition to adatoms, iron clusters are formed, whose density increases drastically at higher coverage and/or deposition temperature. We found dominating clusters of 0.6–0.7 nm (i.e. ~3 atomic layers of Fe) high and ~2 nm wide and islands in their lateral dimensions. According to the DFT results for the system with three iron layers, the chemical interaction decreases compared to adatoms due to the Fe-Fe bonds formation. The clusters are randomly distributed over the surface. However, according to the X-ray photoelectron diffraction data, the ordered structure is formed at the interface, which includes interstitial and surface Fe atoms. Complete surface coverage is realized between 1 and 2 ML. Iron atoms react chemically with Bi_2Te_3 for all considered

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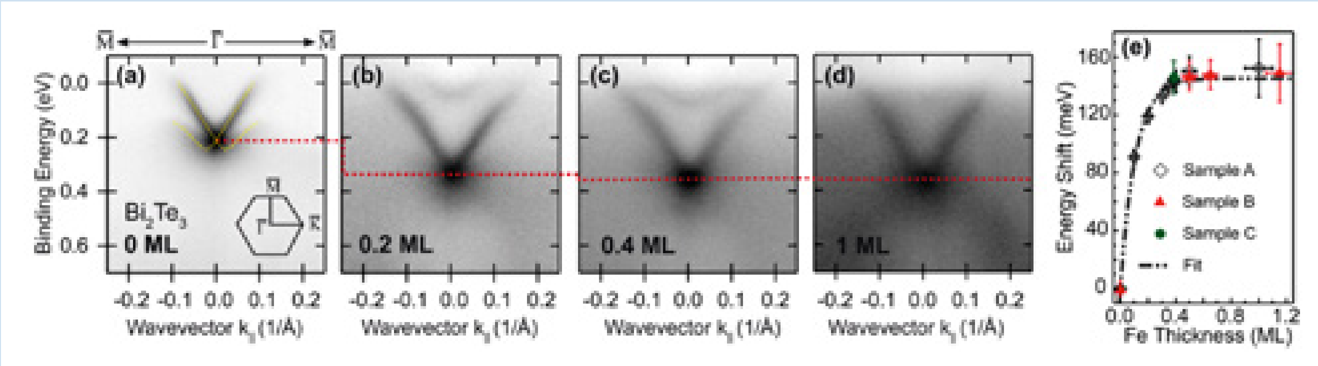

Figure 1. Behavior of the topological upon Fe deposition on Bi2Te3 surface. ARPES data (a-d) show the clean surface and increasing Fe coverage. At about 0.4 monolaeyr the doping reaches saturation (e).

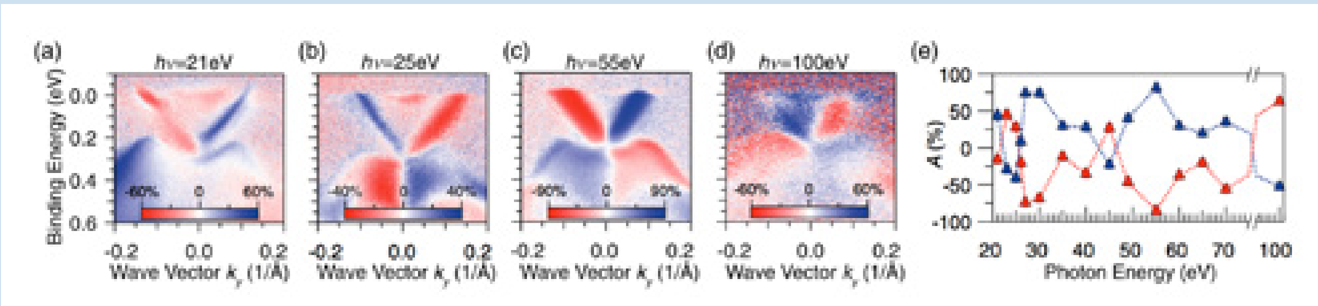

Figure 2. Change of the circular dichroism effect with photon energy – ARPES data

structure (with exception of thick surface layers), forming chemicals bonds to both Bi and Te.

The helical Dirac fermions at the surface of topological insulators show a strong circular dichroism which has been explained as being due to either the initial-state spin angular momentum, the initial-state orbital angular momentum, or the handedness of the experimental setup. All of these interpretations conflict with our data from Bi_2Te_3 which depend on the photon energy and show several sign changes. Our one-step photoemission calculations coupled to ab initio theory confirm the sign change and assign the dichroism to a final-state effect. Instead, the spin polarization of the photoelectrons excited with linearly polarized light remains a reliable probe for the spin in the initial state [2].

To perform further step to practical application the Bi_2Se_3 microflakes we studied in collaboration with Humboldt University of Berlin (Prof. S. Fischer). Temperature dependent transport properties of high-quality exfoliated Bi_2Se_3 microflakes in the crossover regime from thin (>10 nm) to thick (>100 nm) are reported. High resolution transmis-sion electron microscopy and combined energy-dispersive x-ray spectroscopy studies conforms the structure and stoichiometry of bulk and flakes. Angle-resolved photoemission spectroscopy proves single-Dirac-cone surface state and a well-defined bulk band gap in topological insulating state. Here, we demonstrate the usage of spatially resolved core-level photoelectron microscopy to investigate the surface stability of thin topological insulator films. Low temperature transport measurements from 4.2 K to 15 K conforms the high flake quality leading to metallic behavior and weak antilo- calization (WAL), both signatures of the topological properties of surface states. Electron-electron scattering is negligible and electron-phonon scattering is the dominant mechanism in the temper-ature range from 30 K to 280 K. The temperature dependent coherence length indicates that two dimensional conduction is reached in Bi_2Se_3 flakes of 72 nm in thickness. Thickness dependent measurements show that conductance is dominated by surface carriers at low temperatures.

The long-term stability of functional properties of topological insulator materials is crucial for the operation of future topological insulator based devices. Water and oxygen have been reported to be the main sources of surface deterioration by chemical reactions. In the present work, we investigate the behavior of the topological surface states

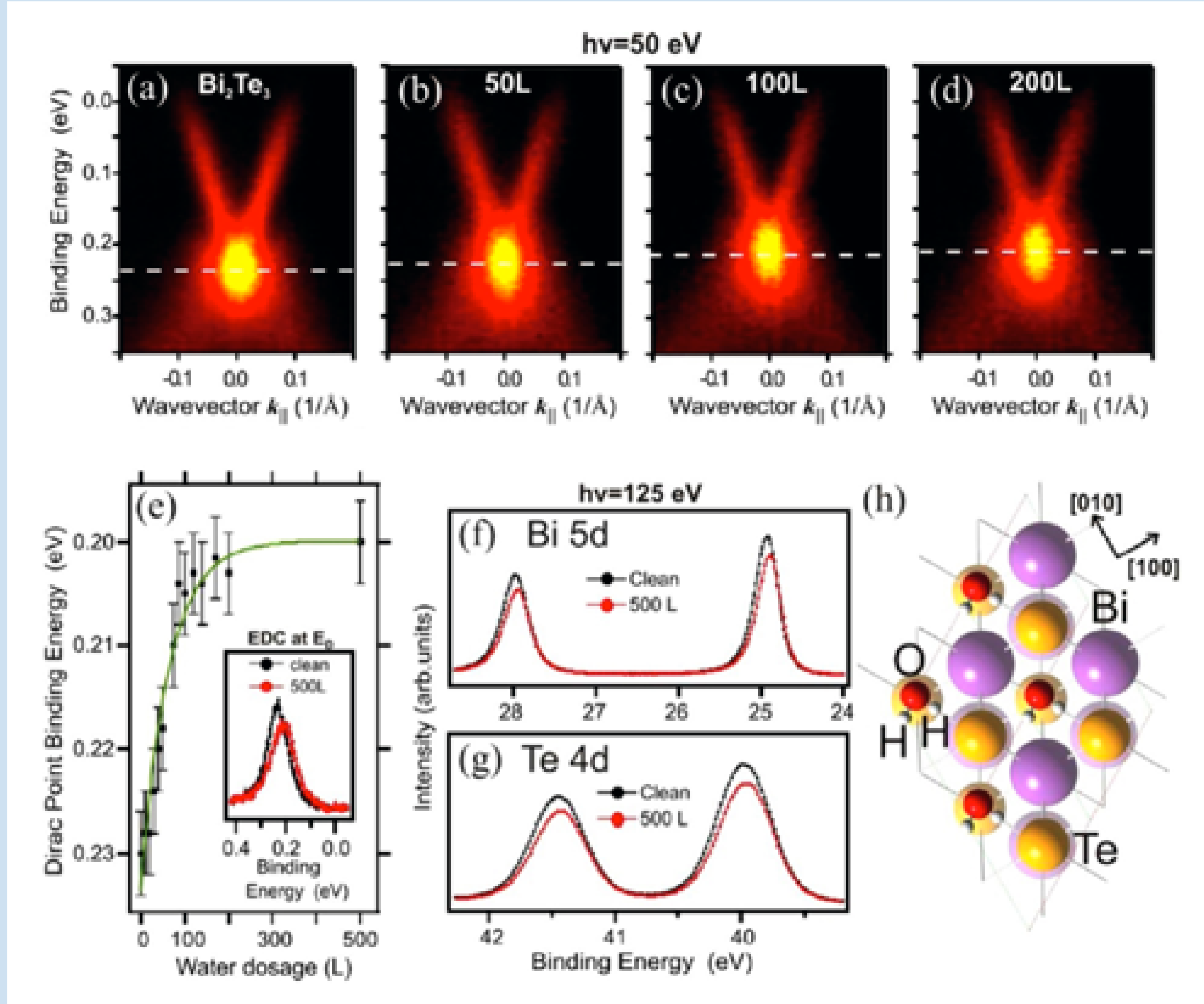

Figure 3. Water exposure of Bi_2Te_3% ARPES data (a-e), XPS data (f,g) and DFT model (h).

on Bi_2X_3 (X = Se, Te) by valence-band and core level photoemission in a wide range of water and oxygen pressures both in situ (from 10^{-8} to 0.1 mbar) and ex situ (at 1 bar). We find that no chemical reactions occur in pure oxygen and in pure water. Water itself does not chemically react with both Bi_2Se_3 and Bi_2Te_3 surfaces and only leads to slight p-doping. In dry air, the oxidation of the Bi_2Te_3 surface occurs on the time scale of months, in the case of Bi_2Se_3 surface of cleaved crystal, not even on the time scale of years. The presence of water, however, promotes the oxidation in air, and we suggest the underlying reactions supported by density functional calculations. All in all, the surface reactivity is found to be negligible, which allows expanding the acceptable ranges of conditions for preparation, handling and operation of future Bi_2X_3-based devices [3].

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