Final Report

Funding Programme:	**Helmholtz Joint Research Groups**
Project ID No.:	HRJRG-400
Project Title:	Application of 3D ellipsoidal cathode laser pulses for high brightness photo injector optimization
Principal Investigator:	Dr. Mikhail Krasilnikov (Helmholtz PI) Prof. Efim Khazanov (Russian PI)

1) Work and Results Report

Please describe the main results and the progress achieved through the Joint Research Group in comparison to the state of the art at the time of writing the application and give an outlook on possible future work and applications.

a) Description of the results (max. 4 DIN A4 pages)

Please describe the scientific and/or technical success of the group as well as secondary results achieved and essential experience gained

A high brightness electron source is a key element for the successful operation of modern linac based SASE FELs, like the European XFEL and FLASH in Hamburg, LCLS at Stanford and others. Photocathode laser pulse shaping is one of the most efficient tools considered for photo injector optimization in many laboratories. For over a decade R&D activities on advanced photocathode laser pulse shaping have been in the core of the research program of the Photo Injector Test facility at DESY in Zeuthen (PITZ). The project "Application of 3D ellipsoidal cathode laser pulses for high brightness photo injector optimization" is regarded as an important milestone towards reaching ultimate performance of the conventional RF photo injectors. A well-established collaboration between DESY (Zeuthen and Hamburg, Germany), Institute of Applied Physics (IAP RAS, Nizhny Novgorod, Russia) and Joint Institute for Nuclear Research (JINR, Dubna, Russia) was utilized to realize the project.

A new Ellipsoidal Laser (ELLA) system has been developed at IAP in frame of the previous collaboration (BMBF project 05K10CHE), then several major improvements were suggested and implemented by IAP experts within this project. The optimization of the second and fourth harmonics generation (WP1) yielded efficiencies of 50% and 20%, correspondingly. A LBO crystal of 4 mm thickness has been used for the second harmonics generation. Initially the fourth harmonics generation was realized using a 4 mm BBO crystal. The concept of angular chirped laser pulses was applied to the optimization of the nonlinear conversion processes. Numerical simulations demonstrated that the angular chirp allows an increase of the frequency conversion efficiency. At the same time this technique preserves a quasi-ellipsoidal shape of the micropulse. Experimental investigations at IAP resulted in energy of the UV micropulses of up to 5 μJ. Detailed numerical studies showed the possibility of further improvement of the fourth harmonics generation. It is important to mention, that for more realistic modeling of the fourth harmonics generation thermal effects and formation of color centers have to be taken into account. Later, utilizing of thinner BBO crystals (2 mm instead of 4 mm) has significantly improved the fourth harmonic generation. Alignment of the laser system at PITZ in 2016 by IAP experts made it possible to obtain 90 mW (30 μJ per micropulse) in IR, 42 mW (14 μJ per micropulse) in green light, and – 3.2 mW (~1 μJ) in UV.

One of the big challenges for the application of the ELLA system at PITZ was integration of the new laser system into the existing accelerator environment. In order to maintain a parallel operation of the existing (developed by Max-Born-Institute, Berlin) and the new

(ELLA) photocathode laser systems (WP6) a significant reconstruction of the PITZ laser room was carried out. Afterwards the new laser system was delivered to PITZ in autumn of 2015. The installation and commissioning of the ELLA laser system was finished by common efforts of PITZ and IAP laser experts in December 2015. The system was successfully integrated into the transport beamline of the primary MBI photocathode laser and used to generate the first photoelectrons from the photocathode in April 2015. These first measurements were asynchronous to the PITZ timing and RF systems. Two resultant issues with device timing were encountered: frequency and phase synchronization of the laser oscillator with the RF phase, and triggering of the Spatial Light Modulators (SLMs). All attempts to correct for the SLM triggering issue by use of an externally triggerable graphics cards or similar methods were not successful. As found out in 2015 the Holoeye SLM installed at first in the system had to be exchanged to avoid time-dependent fluctuations of the reflection coefficient of the device. After first tests done at IAP and detailed discussions with Hamamatsu SLM experts a time-independent SLM (LCOS-SLM Hamamatsu) produced by Hamamatsu was ordered and installed substitutional to the former one from the Holoeye company. In a series of experiments it could be verified that the new SLM fulfills all stability requirements defined by laser and accelerator experts.

The issue of rough oscillator frequency control was solved by external temperature set point modulation, and a piezo-based controller was realized using µTCA technology. As a very precise synchronization of the photo cathode laser compared to the RF of the accelerator is crucial for the operation of facilities like PITZ, FLASH and the European XFEL, a very important task of the project had been the development and afterwards the commissioning of a µTCA timing crate, which allows such very accurately synchronized laser pulse generation within the laser oscillator. These tasks were successfully solved in a close collaboration with experts from the MSK group (DESY, Hamburg). The synchronization works two-level. Rough synchronization can be done by a controlled change of the temperature within the laser oscillator. This allows an accuracy of about few kHz. The fine tuning of the frequency can be done afterwards by applying a voltage to a piezo drum which is embedded in the laser oscillator. At the end of 2016 synchronization tests showed that the µTCA is reliably working 24/7 almost without any disruptions.

A scanning cross-correlator was designed and put into operation for the spatio-temporal diagnostics of the generated UV pulses. The method is based on the nonlinear harmonics generation (4ω-1ω=3ω). The generated UV pulse was scanned by a short IR pulse producing signals from transverse cross sections at different longitudinal locations within the UV pulse. The signal is detected with a photodiode for the intensity distribution and with a speed CCD camera (10 frames in 300 μs) for the 3D shape measurements. Another setup for the 3D laser pulse shape diagnostics was suggested and realized in frames of the project (WP2). It is based on the image-spectrograph principle. It seems to be more robust and implies measurements of a chirped beam in a far field zone using a scanning slit to obtain the corresponding temporal slice. Combining all the slices is resulting in a 3D spectral intensity distribution.

As further development of advanced photocathode laser pulse shaping techniques a method for formation cylindrically symmetric 3D quasi-ellipsoidal laser pulses with help of profiled volume chirped Bragg grating was suggested [18]. A 3D Chirped Bragg Grating (CBG) concept was developed in frames of the working package WP2 (3D laser pulse shape improvement). Volume Bragg gratings, including CBG in photothermorefractive (PTR) glass, are widely used in different lasers thanks to their high diffraction efficiency, high damage threshold, and temperature and optical stability. The refractive index modulation period linearly changes along the direction of light propagation. In this case, different wavelengths are reflected from the grating at different depths, thereby introducing linear frequency modulation (hence, beam shape modification) in the reflected beam. For 3D ellipsoidal beam shaping spatially profiled CBG were fabricated. In such a grating, the region of transverse reflection for each wavelength is a circle with uniform reflection

coefficient. The diameter of the reflection region changes depending on the wavelength (longitudinal coordinate of the grating). At the boundaries of the reflection spectral band of the Bragg grating, the transverse size of the reflection region is minimal and for the central reflection wavelength it is maximal. Such a grating allows controlling the reflected beam diameter as a function of longitudinal coordinate. This coordinate is proportional to time and wavelength. These gratings are referred to as 3D CBGs. They are made of standard CBGs by removing refractive index modulations from the grating areas where reflection is not needed. Reduction of the refractive index modulation amplitude is done by means of ultraviolet radiation with subsequent thermal processing to avoid damage of the produced 3D structure. In the first tests a reflective 3D CBG produced by OptiGrate was used. It has the following parameters: aperture 6x6.3 mm, maximum ellipsoid diameter 6 mm, length 35 mm, central wavelength 1029.9 nm, FWHM spectral band 5 nm, and stretching factor 63.3 ps/nm. The results of these first experiments – the shape of the beam reflected from CBG and reconstructed from the image spectrograph data - are presented in Fig. 1 for cylindrical (left) and 3D ellipsoidal pulse. Still the ellipsoidal pulse duration is much longer than the goal values, but there is no principal limitation to achieve the specs. Further studies are ongoing within the established collaboration. Besides the above mentioned laser pulse shapes it has been found that the developed laser system is capable to generate other pulse shapes like triangular-profiled pulses which are of particular interest for plasma wake field experiments.

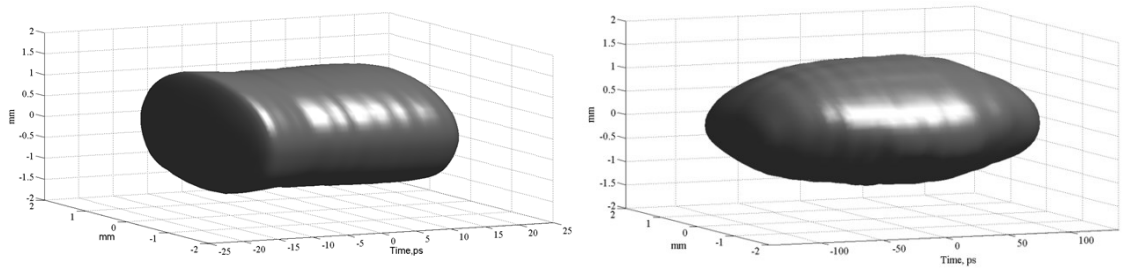

Fig. 1: Left: 3D distribution of cylindrical beam incident on CBG. Longitudinal beam scale – 40 ps (the spectrum changes within 1029.9±2.75 nm). Right: 3D distribution of ellipsoidal beam. Longitudinal beam scale – 264 ps (the spectrum changes within 1029.9±2.5 nm).

Electron bunch shape diagnostics with respect to the photocathode laser pulse shape is one of the important work packages of the project (WP5). Corresponding beam dynamics simulations on the measurement procedure have been performed. As a benchmark input beam dynamics simulations (WP3) for three photocathode laser shapes (Gaussian longitudinally and uniform transversely; flattop longitudinally and uniform transversely; 3D ellipsoid) have been used. Simulations of the longitudinal profile measurement using a Transverse Deflecting Structure (TDS) have been performed for the three above mentioned laser pulse shapes. The current profile measurement of the ELLA laser generated beam is similar to a Gaussian shape, which indicates that the current profile is probably not well suited for laser tuning. It is clear that the beam profile on a screen after the streaking with the TDS is a very good estimation of the beam side view. Obviously, the differences between the electron beams generated from the 3 different laser pulse shapes are much stronger looking at 2D distributions (t ,x) downstream the TDS (with TDS on) than just only bunch current profile analyses.

Numerous beam dynamics simulations were performed in order to study the possibility to utilize high quality electron beams from the PITZ photo injector for scientific and industrial applications, like THz generation and extreme nanolithography (WP7). As part of the beam diagnostics as well as a possible application of the new photocathode laser system THz generation by specially shaped electron bunches is under study at PITZ [7]. In 2016 experimental characterization and optimization of electron beams generated by the MBI laser system have been performed as preparation studies for specially shaped bunch generation from the ELLA system. Investigations on the capabilities of IR/THz production at

the PITZ facility were conducted. The IR/THz radiation generated by means of SASE FEL, Coherent Transition Radiation (CTR) and Coherent Diffraction Radiation (CDR) have been considered and studied. A long-Gaussian electron beam (~10 ps FWHM) with a peak current of ~200 A is used for the studies of the SASE FEL option [21, 22]. Electron beams with short-Gaussian (<2 ps FWHM) and comb-like longitudinal profiles are used for studies of the CTR and CDR options [12].

One important task towards generation of 3D quasi-ellipsoidal electron bunches was integration of the new laser system into the transport beam line to the photocathode (WP4). In fact, the default (MBI laser system) transport beam line aims to produce radially homogeneous transverse laser profiles by imaging of zoomed cylindrical pulses with Gaussian transverse distribution onto so-called beam shaping aperture (BSA) which truncates only the central part of the beam. This telescope setup is shared by both laser systems, whereas the transverse cut with BSA cannot be applied for ELLA pulses. Optical matching of the new laser system into the existing transport beam line had unfortunately only limited success (due to the introduced additional aberrations).

Finally, after the above mentioned problems were solved or at least alleviated it was possible to perform the characterization of electron beams generated with the new photocathode laser system. Electron beam measurements with the new photocathode laser system utilized a “truncated” beam owing to the imperfect transport of the laser to the cathode resulting in a large transverse spot size on the cathode. This was observed with a camera (VC2) placed at a virtual plane with an optically equivalent distance to the photocathode as that of the real beam path (Fig. 2, left). As the new photocathode laser system “piggybacks” onto the already existing laser transport beamline it was possible to achieve the desired dimensions by cropping the beam with the BSA diameter set to 1.2 mm (Fig. 2, middle). The SLM mask was manually fitted by observation of the IR cross-correlation to obtain a 10-12 ps FWHM distribution as a first approximation. This reduced temporal length can be explained by the dip in the laser spectrum, shown in Fig. 2, right plot (black curve).

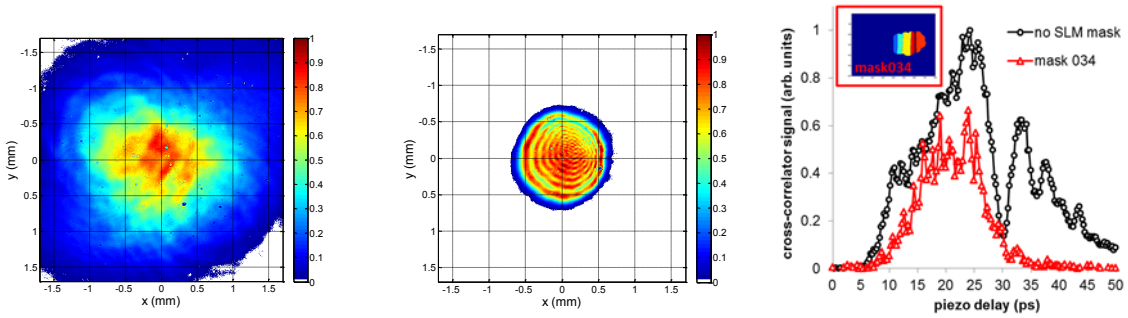

Fig. 2: Transverse laser profile at a virtual cathode plane without (left) and with (middle) a beam shaping aperture. Laser temporal envelope obtained by infrared cross-correlation (right).

The emittance of the generated electron beam was measured for 0.5 nC bunch charge, under the machine parameters obtained from corresponding beam dynamics simulations [23]. The transverse normalized projected emittance has been measured using the standard slit scan technique applied at PITZ. The measured beam emittance is shown in Fig. 3 together with the rms beam sizes as a function of main solenoid current.

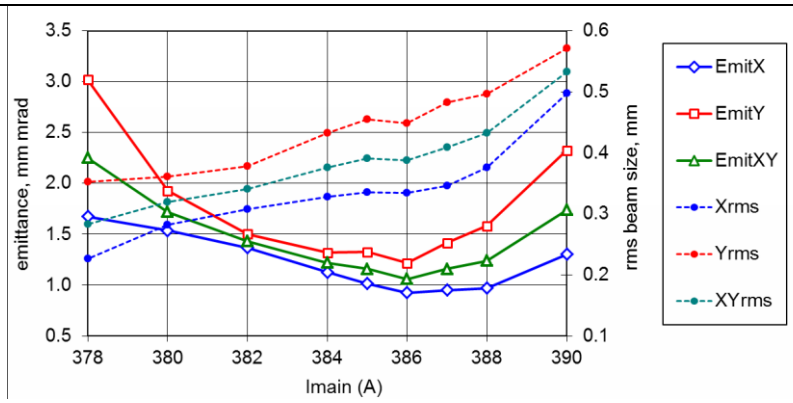

Fig. 3: Measured electron bunch emittance and spot size as a function of main solenoid current.

The normalized transverse emittance at the optimum solenoid current (386 A / 225 mT) was found to be ε_{nx}=0.93 mm mrad, ε_{ny}=1.22 mm mrad, and a geometric mean of ε_{nxy}=1.06 mm mrad. These values are on par with measurements undertaken for the nominal flat-top photocathode laser pulses. Corresponding electron beam distributions are shown in Fig. 4.

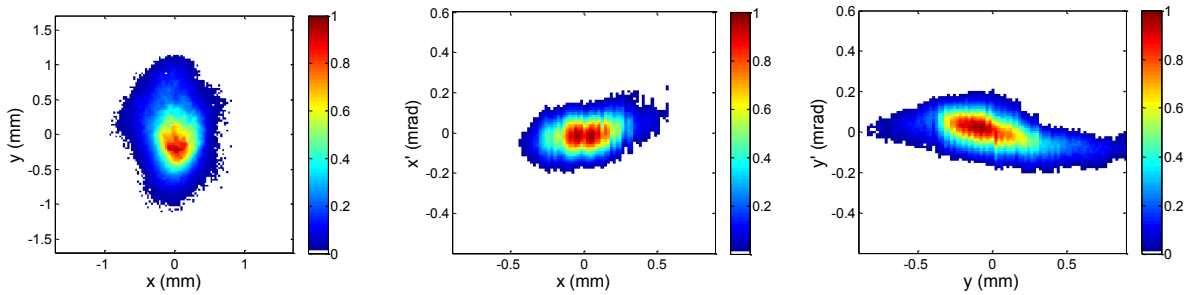

Fig. 4: Measured electron beam distributions: left – transverse (x-y), middle – horizontal phase space (x-x'), right - vertical phase space (x-x').

The beam was also observed with the a transverse deflecting cavity and seen to have a close-to parabolic current density (Fig. 5, left) and a roughly ellipsoidal shape on the temporal transverse x coordinate plane (Fig. 5, right).

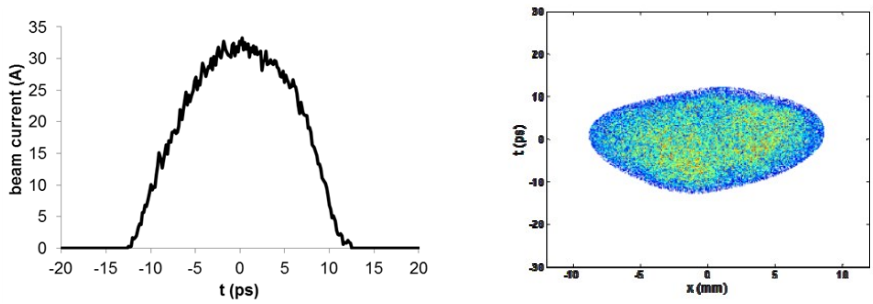

Fig. 5: Measured beam current profile with a TDS (left), measured distribution of the electron beam vertically streaked by the TDS.

b) Outlook on future work, sustainability (max. 2 DIN A4 pages)

How far did the JRG intensify the scientific cooperation between Helmholtz and international partners? Did it set new impulses in existing and upcoming research programmes of the Helmholtz Association? Does it form the core of a future, larger scale bilateral or otherwise funded project? Please describe planned activities/ cooperations to further develop the work, if applicable also with additional partners.

Experiences with the prototype have shown that significant upgrades of the laser system are needed in order to facilitate the installation of such a system at a full-time user facility, such as FLASH and the European XFEL. The original ELLA system delivered by IAP suffers from a number of system limitations. As such a redesign was undertaken to address these limitations. The primary system issues are as follows:

- Poor pointing stability due to a combination of humidity-induced thermal drift from the oscillator and poor optomechanical stability
- Poor spectro-temporal/transverse quality resulted in a restriction of the usable bandwidth, and by extension, the useable area of the SLM chip, thereby reducing the resolution of the mask
- Transverse distortion from the amplification process of the thin-disc amplifier, the stability of the pump laser on the gain medium and of a significant number of optical elements

These system issues are addressed primarily by replacing the oscillator - preamplifier with a high-power, commercial Pharos oscillator-amplifier laser system from Light Conversion. This permits a linearized simplification of the pulse shaping scheme thereby significantly reducing the number of optical elements and the optical path length. This reduces the influence of the pointing stability through the system, lens and alignment errors, and simplifies observation of the laser chain status, and realignment. All unsolved problems from the first ELLA setup (like pointing stability, usable SLM area issues and amplification impact onto the transverse laser profile) are addressed to the overall redesign. The setup of the upgraded photocathode laser system based on the Pharos laser is shown in Fig. 6.

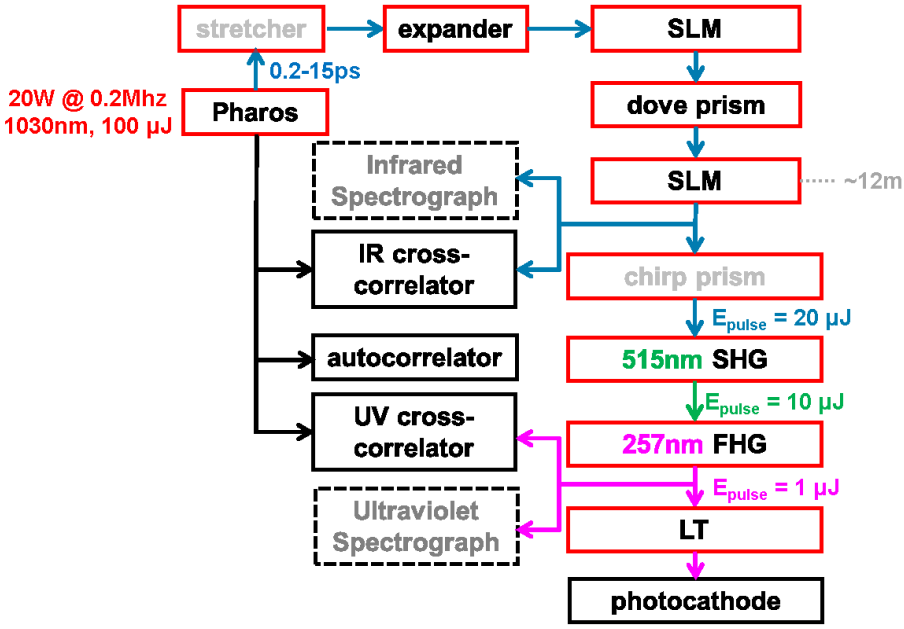

Fig. 6: Simplified block diagram scheme of the laser upgrade

As a first step a new laser oscillator Pharos (PH1-20-0200-10-N2-NS) has been purchased from the project budget and has been delivered to PITZ in spring 2017. First on-table tests are encouraging. This industrial laser has several advantages: an amplifier is included which possibly avoids the disc-amplifier currently used, the laser pulse frequency and the number of micro-bunches can be easily changed via the control system, 2nd and 4th harmonics generation is possible without changing the system (which makes it useful also as a backup laser). Also, the experience on the timing synchronization gained from the current system will be reused.

One of major results of the project is a pulse shaper upgrade by using volume Bragg gratings for obtaining rotationally symmetric shapes of the laser pulses. This technology opens new possibilities in advanced pulse shaping and already attracted interest from the

accelerator community. It is considered as an option for the photo injector of the European XFEL as well as other facilities (e.g. triangle laser pulses for electron drivers in plasma wakefield experiments). This finding gave a new impulse in the laser activities at DESY. There is a dedicated DSF (DESY Strategy Fund) project "Spatiotemporal shaping of ellipsoidal laser pulses with profiled volume Bragg gratings" currently running at PITZ.

Also a possibility to use the developed pulse shaping techniques for generating electron bunches with controllable temporal modulation is of great interest for the accelerator community. A possibility to use such beams for generation of seeded high intensity THz radiation in undulators is under studies now. This is of particular interest for pump-probe experiments extending the applicability of the project results to the FEL user community.

The upgraded ELLA setup enables also other studies at PITZ. High variability and flexibility (laser pulse length and energy) makes it possible to use it for detailed studies of photoemission processes in high brightness RF guns. This was and remains a key issue for the detailed understanding of the space charge dominated beam dynamics in modern photo injectors.

The project has established a close collaboration between partners. Numerous meetings, video conferences, mutual visits for knowhow exchange have brought laser and accelerator experts together resulting in synergy between both communities. This ensures also further collaboration between the project partners. During the course of the project Russian partners IAP RAS and JINR signed the PITZ MoU in 2015 and became official members of the PITZ collaboration (in total 12 international partners now).

c) Potential for application/exploitation (max. 2 DIN A4 pages)

How do you yourself assess the potential for application or exploitation of the results? Where do you see future possibilities? Please describe realized or planned measures for applying the results. Please also include information on patents, licenses, co-operations with industry, etc.

The new upgraded ELLA photocathode laser system is integrated in the PITZ accelerator complex and is going to be in parallel operation with the MBI laser system. An advanced photocathode laser pulse shaping (3D ellipsoid) towards generating ultimate low emittance is in the core of the PITZ generic R&D on high brightness photo injectors supported by the European XFEL and allows operation beyond current specs. Also the potential for improved beam quality at reduced cathode gradient if of crucial importance for obtaining the required beam quality for a future CW operation of the European XFEL.

As an upcoming upgrade of the ELLA laser system the volume Bragg grating based laser pulse shaping is considered. Corresponding activities in the frame of the corresponding DSF project are ongoing at PITZ. Experience gained from the project is strengthening photocathode laser expertise at the facility. Several technological aspects (like μTCA technology for the synchronization of the laser with RF) are of practical application.

After the ELLA laser system confirms the advantages of the advanced pulse shaping and demonstrates its feasibility for routine operation there are definite perspectives of application of the developed technology at user facilities, like the European XFEL and FLASH at DESY in Hamburg as well as at other FEL facilities worldwide.

Developments within the project towards generation of triangle photocathode laser pulses are of definite interest for other photo injector applications, e.g. for its usage in plasma wakefield acceleration experiments. Production of the triangle driver electron beams is under intensive studies at several accelerator laboratories around the world. Also advanced photocathode pulse shaping (e.g. with controllable modulation of intensity) is of definite interest for photo injector baser FEL sources (seeded FELs).

Studies on 3D pulse shaping performed in the frame of this project stimulated a progress in the ps laser technology. The concept of the 3D Chirped Bragg Grating (or Volume Bragg Grating) was suggested and realized in a close collaboration with industrial partners

(OptiGrate, Oviedo, Florida, USA). Also contacts to other industrial partners (HOLOEYE Photonics AG and Hamamatsu Photonics) served for synergy of advanced research and serial production facilities. There might be a potential to use advanced laser pulse shaping techniques also for other applications, e.g. laser material processing for industry and medical instrumentation.

2) Qualification of Junior Researchers (max. 2 DIN A4 pages)
Please describe the main achievements regarding personal qualifications (Diploma, bachelors or masters degrees, conferring of doctorates, "habilitations", appointments/junior professorships, etc.). How far have new career perspectives for young scientists inside the foreign country been developed?

Two PhD students were fully funded in the frame of the project (Helmholtz site). They have been actively involved in the project realization.

In spring 2015 James Good has started his work on the subject "Experimental characterization of the photocathode laser system for advanced 3D pulse shaping at PITZ". A majority of working packages of the project belongs to the scope of his PhD thesis. He has developed himself to the expert level in the field. His primary task was to integrate, operate, and characterize the prototype IAP laser system at PITZ. James made significant efforts for the integration of the new system into the PITZ sub systems; the video system, the μTCA-based synchronization system, and diagnostics and control systems. Over the course of the project he encountered and overcame a number of operational issues; damaged amplifier crystals, water cooling system issues, temporal instability of key reactive components, pump laser instability, optomechanic instability, remounting of non-linear crystals, etc. Furthermore a number of milestones were reached: first photoelectrons were generated in late 2015, and owing to the integration of a μTCA-based system to synchronize the laser oscillator with the RF in the gun, synchronized photoelectrons were generated in late 2016. Pulse shaping was observed and preliminarily characterized using IR cross-correlator and IR spectrograph. Additionally, he has spearheaded the design and development of spectrographs, a drift correction system, and the optical layout for a new commercially-based photocathode laser system for PITZ. The characterizing spectrographs, in both IR and UV, have been designed, components acquired, and initially brought into operation in the IR. A number of particularly large steps have been made in the last few months in a number of directions with the commissioning of the spectrograph, implementation of the drift correction, routine pulse shaping, and the purchase of a new frontend laser. Using gained knowhow and experience James made a significant contribution to the above mentioned significant upgrade of the ELLA laser system. One of his recent tasks was commissioning of the new commercial Pharos oscillator-amplifier laser system. James has participated in a number of meetings and workshops. He has produced a variety of talks, posters and proceedings for FEL 2015 and 2017, German Physics Society meetings 2015 and 2016 (DPG Frühjahrstagungen), 3rd ARD ST3 workshop etc. He also completed the exam at the U.S. Particle Accelerator School in January 2016 at Austin, USA, while attending the course "Fundamentals of Accelerator Physics and Technology". James also became a certified matlab expert which helped a lot for the commissioning of the new laser system.

Another PhD student – Prach Boonpornprasert, works on the topic "Investigations on the capabilities of THz production at the PITZ facility", which is assumed to be important part of the project. He studied a possibility to use advanced photocathode laser pulse shaping to generate IR/THz radiation by electron bunches from a PITZ-like linear accelerator. Such studies are of great importance for pump and probe experiments at the European XFEL. The same pulse structure at PITZ and at the European XFEL provides the possibility to produce trains of THz pulses well-synchronized to the corresponding x-ray pulses. Prach has studied two options to produce THz radiation from electron beams at PITZ. The first option is based on the Self Amplified Spontaneous Emission of Free-Electron Lasers (SASE FELs) in an APPLE-II type

undulator using high charge (~4 nC) electron bunches from the PITZ photo injector. Coherent Transition Radiation (CTR) using a short electron bunch compressed by velocity bunching is assumed for the second option. Prach Boonpornprasert has performed start-to-end simulations using ASTRA and GENESIS codes to estimate properties of the SASE radiation for the wavelength range of 20-100 um, including pulse energy and spectrum evaluation. Also simulations of velocity bunching using the booster cavity at PITZ were performed to calculate expected CTR spectrum and evaluate THz pulse energy. Prach has summarized these preliminary studies in numerous talks, posters and conference proceedings, like FEL 2014, FEL 2015, FEL 2017, German Physics Society meetings 2014, 2015, 2016 and 2017 (DPG Frühjahrstagungen), 3rd ARD ST3 workshop etc. His talk "Simulations of IR/THz Options at PITZ (High-gain FEL and CTR)" at the DESY Beschleuniger Ideenmarkt in September 2015 has received very positive feedback. Prach has written a "Status report on studies of THz options at PITZ" which has been delivered to the colleagues at the European XFEL to be discussed with the user community. In order to demonstrate the ability to generate electron beams used in the THz simulations a corresponding experimental program was realized at PITZ starting in 2015. Prach has coordinated the measurement program for high charge electron beam characterization as well as bunch length measurements for a moderate bunch charge while applying velocity bunching. This was the first high charge beam characterization at PITZ, resulting in transverse and longitudinal phase space measurements of a 4 nC electron beam using the slit-scan technique for emittance measurements, the transverse deflecting system (TDS) for bunch temporal profile determinations and the TDS together with the second high energy dispersive arm (HEDA2) for longitudinal phase space measurements. Prach Boonpornprasert has summarized these experimental studies and presented it at several seminars and meetings. He has participated in the U.S. Particle Accelerator School in January 2016 at Austin, USA, attending the course "Classical Mechanics and Electromagnetism".

Both PhD students became active members of the PITZ team, have participated actively in the measurement shifts and have been promoted to shift leaders for the PITZ operation.

Also there is a significant development of young researcher at the Russian institution sites. The work of IAP PhD student Ekaterina Gacheva was awarded with a stipendium of regional Ministry of Education (academician G. A. Razuvaev's stipendium 2013-2014). She had defended in 2015 her PhD Thesis "Управление параметрами лазерных драйверов для фотоинжекторов ускорителей электронов" (Control of laser driver parameters for photo injectors). This work summarizes the ELLA laser system developments at IAP. Another young IAP researcher – Sergey Mironov was awarded with a Stipendium of the President of the Russian Federation for young Russian scientists (SP-2089.2015.2). The IAP group of E. Gacheva, S. Mironov and A. V. Andrianov has been also awarded in 2016 with the diploma of the third degree of XVIII contest for young scientists of the Institute of Applied Physics RAS for the work "Formation of 3D ellipsoidal laser beams in cathode lasers".

Numerous mutual visits of young scientists in the course of the project served to the intensive exchange of the knowhow and experimental skills:

- 02.06–06.06.2014 and 04.08–09.08.2014 – PITZ researchers visited IAP to learn the new laser system
- 06.10–07.12.2014 – IAP researched visited PITZ for the new laser system installation
- 16.03–22.03.2015 and 05.10–16.10.2015 – IAP experts visited PITZ for the laser system commissioning
- 21.11-29.11.2016 – IAP experts visited PITZ for the laser system tuning and first experiments with electron beams

3) Public relations

By which means did you gain publicity (e.g. reporting in media, own website)?

Results and the status of the project were reported at many conferences and meetings:

- 2nd ARD ST3 workshop, HZDR, Dresden-Rossendorf, 26-27.02.2014, Talk of M. Krasilnikov “Advanced photo cathode laser pulse shaping for ultimate XFEL photo injector performance” (Activities at PITZ in the frame of ARD-ST3 “ps – fs Electron and Photon Beams”)
- HRJRG Workshop, March 3, 2014, Moscow. Talk of M. Krasilnikov “Development of a photo cathode laser system for quasi ellipsoidal bunches at a high brightness photo injector”
- IPAC 2014, June 18, 2014, Dresden, Poster of T. Rublack “Development of a Quasi 3-D Ellipsoidal Photo Cathode Laser System for PITZ”
- IPAC 2014, June 18, 2014, Dresden, Poster of M. Khojoyan “Studies on the application of the 3d ellipsoidal cathode laser pulses at PITZ”
- Laser Optics 2014 (16th International Conference on Laser Optics), St. Petersburg, Russia, 30.06-04.06.2014, Invited talk of S. Mironov “Laser system for generation 3D ellipsoidal UV pulses”
- 4th German-Russian Young Researchers Forum, St. Petersburg, Russia, July 9, 2014, Talk of T. Rublack “Development of a quasi 3D ellipsoidal laser system at IAP RAS for the high brightness photo injector at PITZ”
- FEL 2014, August 28, 2014, Basel, Poster of T. Rublack “Design of a spatio-temporal 3-D ellipsoidal photocathode laser system for the high brightness photoinjector PITZ”
- FEL 2014, August 28, 2014, Basel, Poster of M. Khojoyan “Optimization of the PITZ Photo Injector Towards the Best Achievable Beam Quality”
- DPG-Frühjahrstagung, Wuppertal, Germany, March 9–13, 2015:
  P. Boonpornprasert et al., “Start-to-End Simulations for a 100 µm SASE FEL at PITZ”
  J. Good et al., “Preliminary Results from the Laser System generating Quasi 3-D Ellipsoidal Photocathode Laser Pulses at PITZ”
- IPAC15, Richmond, Virginia, USA: May 3–8, 2015: T. Rublack et al., “First Results Attained With the Quasi 3-D Ellipsoidal Photo Cathode Laser Pulse System at the High Brightness Photo Injector PITZ”, poster.
- LPAW2015, Guadeloupe, France: May 10–15, 2015: F. Stephan et al., “Photo Cathode Laser Pulse Shaping for Generating Ultimate Electron Beam Quality”, poster.
- 3rd ARD ST3 Workshop, Karlsruhe, Germany: July 15–17, 2015: P. Boonpornprasert, M. Krasilnikov et al., “Simulations of the IR/THz Options at PITZ (High-gain FEL and CTR)”, talk and poster.
- Ultrafast optics 2015, Beijing, China, August 16-21, 2015. E.A. Khazanov, "Generation of 3D quasi-ellipsoidal chirped infrared laser pulses", talk
- FEL2015, Daejeon, Korea: August 23–28, 2015:
  M. Bakr et al., “Beam Dynamics Simulation for the Upgraded PITZ Photo Injector Applying Various Photocathode Laser Pulses”, poster.
  P. Boonpornprasert et al., “Numerical Simulations of a Sub-THz Coherent Transition Radiation Source at PITZ” poster.
  J. Good et al., “New Ellipsoidal Laser at the upgraded PITZ Facility”, poster.
- DESY Beschleuniger Ideenmarkt, Hamburg: 1-2 September, 2015: P. Boonpornprasert “Simulations of the IR/THz Options at PITZ (High-gain FEL and CTR)”, talk
- EAAC2015, La Biodola, Isola d'Elba, Italy: September 13–19, 2015: T. Rublack et al., , “Production of quasi-ellipsoidal laser pulses for next generation high brightness photoinjectors”, poster
- Nonlinear waves-2016, Nizhniy Novgorod, Russia, 27.02-04.03.2016. M. Krasilnikov “High brightness RF photo injectors for modern Free Electron Lasers.”
- 2nd Annual MT Meeting, Karlsruhe: 8 - 10 March 2016. P. Boonpornprasert et al., „First Experimental Characterization of Electron Beams for THz Options at PITZ
- DPG-Frühjahrstagung (Spring Meeting), Darmstadt: 14-18.03.2016. P. Boonpornprasert et al., „First Characterizations of a 4 nC Electron Beam for THz Options at PITZ”

C. Saisa-ard et al., “Evaluation of the Photocathode Laser Transverse Distribution”

- Senior scientific researcher qualification seminar, IAP RAS, June 2016. S. Mironov "Control of spatial and spectral-temporal parameters of femtosecond laser pulses"
- 3rd Annual MT Meeting, GSI, Darmstadt: 31 January 2017. P. Boonpornprasert et al. “Electron Beam Characterizations for Generating THz Radiation with PITZ”.
- Annual RAS meeting, Division of Physics session, 1 of March 2017. S. Mironov et al., "Spatio-temporal shaping of photocathode laser pulses for linear electron accelerators"
- DPG-Frühjahrstagung (DPG Spring Meeting), Dresden, 19 - 24 of March 2017. P. Boonpornprasert et al., “Experimental Optimization of Electron Beams for Generating THz Coherent Transition and Diffraction Radiations with PITZ”, talk.
- IPAC 2017, Copenhagen, Denmark: 14-19 May 2017. P. Boonpornprasert et al., “Experimental Optimization and Characterization of Electron Beams for Generating IR/THz SASE FEL Radiation with PITZ”, poster
- FEL 2017, Santa Fe, New Mexico, USA: 20-25 August 2017.
  P. Boonpornprasert et al., „Calculations for a THz SASE FEL Based on the Measured Electron Beam Parameters at PITZ“, poster
  J.D. Good et al., “Preliminary On-Table and Photoelectron Results from the PITZ Quasi-Ellipsoidal Photocathode Laser System”, poster.

4) Networking

What co-operation and communication structures have been developed during the course of the funding? What is the contribution of the group to the networking of international partners and the Helmholtz Centre(s)?

The collaboration between PITZ (DESY) IAP RAS and JINR has been further developed. Numerous project collaboration meetings were organized in order to intensify knowledge and skills exchange:

- 02.06. – 06.06.2014 at IAP/RAS, Nizhny Novgorod, Russia
- 04.08. – 09.08.2014 at IAP/RAS, Nizhny Novgorod, Russia
- 17.03.2015 at DESY, Zeuthen (PITZ)
- 03.06.2015 at DESY, Zeuthen (PITZ)
- 12.10.2016 at DESY, Zeuthen (PITZ)
- 24.11.2015 at DESY, Zeuthen (PITZ)
- 04.03.2015 at IAP RAS, Nizhniy Novgorod
- 13.04.2016 Videoconference DESY(Zeuthen and Hamburg) -IAP
- 22.11.2016 at DESY, Zeuthen (PITZ)
- 14.12.2016 Videoconference DESY-IAP

In order to realize the project tasks several cooperation structures were established additionally to the above mentioned DESY-IAP-JINR collaboration. Several laser technological issues were solved together with experts from the FS-LA (DESY, Hamburg) group. Close collaboration with MSK DESY group has been developed in order to implement μTCA based synchronization of the new laser system to the PITZ RF gun power feed.

The PITZ project is based on collaboration with includes many institutions from Germany (including Helmholtz centers – HZB and HZDR) and abroad. The status of the project “Application of 3D ellipsoidal cathode laser pulses for high brightness photo injector optimization” has been reported at numerous PITZ collaboration meetings:

- DESY, Zeuthen, 27-28.05.2014, Talks of T. Rublack “Installation of 3D ellipsoidal laser system” and of P. Boonpornprasert “Beam Dynamics Simulations for Undulator Radiation of IR/THz Source Project at PITZ”
- DESY, Zeuthen, 2-3.12.2014
  Talk of S. Mironov “Laser system for generation 3D ellipsoidal UV pulses”
  Talk of M. Khojoyan “3D ellipsoidal laser pulses: summary of electron beam studies”

Talk of P. Boonpornprasert “Start-to-End Simulation of THz FEL with Actual PITZ Beamline”

- PITZ Collaboration Meeting, June 2-3, 2015:
  M. Nozdrin, “Joint Institute for Nuclear Research and its activity in FEL”, talk
  T. Rublack, “Status of laser system for 3D ellipsoidal laser pulse shaping”, talk
  E. Khazanov, “Review of Photocathode laser driver activity in Institute of Applied Physics”
- PITZ Collaboration Meeting, November 24-25, 2015.
  S. Mironov “3D ellipsoidal laser beams in IAP RAS”, talk
  J. Good, “Laser System for Generation of Quasi Ellipsoidal Pulses – Status Report”, talk
  P. Boonpornprasert, “First experimental characterization of electron beam for THz options at PITZ”, talk
  G. Shirkov, “Basic Facilities and New Projects at JINR”, talk
- PITZ Collaboration Meeting, Zeuthen, 31.05-01.06.2016.
  E. Khazanov "Photocathode laser developments",
  J. Good “Laser System for Generation of Quasi Ellipsoidal Pulses”
  M. Nozdrin “JINR: e-Linac and Photoinjector Activities”
- PITZ Collaboration Meeting, Zeuthen, 29.11-30.11.2016
  S. Mironov "Laser pulse shaping activity in IAP RAS"
  J. Good “ELLA status”
- PITZ Collaboration Meeting, Zeuthen, 13.06-14.06.2017
  P. Boonpornprasert “Design of the THz CTR/CDR Station at PITZ”
  S. Mironov “Formation triangular laser pulses at IAP RAS”
  J. Good “Ellipsoidal Laser Status & Results”

Results of the project have been presented at the workshop “Perspectives on Photocathode Lasers for Photo Injectors” held at HZDR on 11.04.2017.

5) List of Publications

Articles in scientific journals, written contributions to scientific meetings, contributions to books, other publications.

[1] A.K. Poteomkin, A.V. Andrianov, E. Gacheva, V. Zelenogorsky, S.Y. Mironov, E.A. Khazanov, M. Martyanov, E.M. Syresin, M. Krasilnikov, F. Stephan, "Generation of 3D ellipsoidal shaped UV laser pulses for the future XFEL low-emittance photo-injector", SPIE Optics+Optoelectronics, High- Power, High-Energy, and High-Intensity Laser Technology (Conference 8780A), Proceedings of SPIE Volume 8780A, 2013, 28.

[2] M. Khojoyan, M. Krasilnikov, F. Stephan, G. Vashchenko, „Beam dynamics optimization for the high brightness PITZ photo injector using 3D ellipsoidal cathode laser pulses“in Proceedings of the 35th International Free-Electron Laser Conference, New York, NY, USA, pp.298-302.

[3] M. Krasilnikov M. Khojoyan, F. Stephan, A. Andrianov, E. Gacheva, E. Khazanov, S. Mironov, A. Poteomkin, V. Zelenogorsky, E. Syresin, “Development of a photo cathode laser system for quasi ellipsoidal bunches at PITZ”, in Proceedings of the 35th International Free-Electron Laser Conference, New York, NY, USA, pp.303-308.

[4] M. Krasilnikov et al., “PITZ experience on the experimental optimization of the rf photo injector for the European XFEL” in Proceedings of the 35th International Free-Electron Laser Conference, New York, NY, USA, pp.160-168.

[5] E. Khazanov, A. Andrianov, E. Gacheva, G. Gelikonov, V. Zelenogorsky, S. Mironov, A. Poteomkin, M. Martyanov, E. Syresin, M. Krasilnikov, and F. Stephan, "Cross-Correlator for the Diagnostics of 3D Ellipsoidal Shaped UV Laser Pulses for XFEL Ultra Low-Emittance Photoinjector," in CLEO: 2013, OSA Technical Digest (online)

(Optical Society of America, 2013), paper JTh2A.27

[6] V.V. Zelenogorskii, A.V. Andrianov, E.I. Gacheva, G.V. Gelikonov, M. Krasilnikov, M.A. Mart'yanov, S.Yu. Mironov, A.K. Potemkin, E.M. Syresin, F. Stephan, E.A. Khazanov, "Scanning cross-correlator for monitoring uniform 3D ellipsoidal laser beams", Quantum Electronics 44 (1) 76 – 82 (2014)

[7] E. Syresin, S. Kostromin, M. Krasilnikov, R. Makarov, N. Morozov, D. Petrov, THz Wiggler Applied for Measurements of Electron Bunch Longitudinal Structure in FEL, Physics of Particles and Nuclei Letters, 2015, Vol. 12, No. 1, pp. 118–121.

[8] E. I. Gacheva V. V. Zelenogorskii, A. V. Andrianov, M. Krasilnikov, M. A. Martyanov, S. Yu. Mironov, A. K. Potemkin, E. M. Syresin, F. Stephan, E. A. Khazanov, "Disk Yb:KGW amplifier of profiled pulses of laser driver for electron photoinjector", Optics Express Vol. 23, Issue 8, pp. 9627-9639 (2015).

[9] F. Stephan, M. Krasilnikov, "High Brightness Photo Injectors for Brilliant Light Sources", Chapter of the book "Synchrotron Light Sources and Free-Electron Lasers", editors E. Jaeschke, S. Khan, J.R. Schneider, J.B. Hastings, Springer International Publishing Switzerland, ISBN 978-3-319-04507-8.

[10] T. Rublack, J. Good, M. Khojoyan, M. Krasilnikov, F. Stephan, I. Hartl, S. Schreiber, A. Andrianov, E. Gacheva, E. Khazanov, S. Mironov, A. Potemkin, V. V. Zelenogorskii, E. Syresin, "First Results Attained With the Quasi 3-D Ellipsoidal Photo Cathode Laser Pulse System at the High Brightness Photo Injector PITZ", Proceedings of the sixth International Particle Accelerator Conference, Richmond, Virginia, USA, 2015, TUPWA047.

[11] M. Bakr, G. Vashchenko, M. Khojoyan, M. Krasilnikov, F. Stephan, "Beam Dynamics Simulation for the Upgraded PITZ Photo Injector Applying Various Photocathode Laser Pulses", Proceedings of the 37th International Free Electron Laser Conference, Daejeon, Korea, 2015, TUP065.

[12] P. Boonpornprasert, M. Krasilnikov, F. Stephan, B. Marchetti, "Numerical Simulations of a Sub-THz Coherent Transition Radiation Source at PITZ" Proceedings of the 37th International Free Electron Laser Conference, Daejeon, Korea, 2015, MOP033.

[13] J. Good, G. Asova, M. Bakr, P. Boonpornprasert, M. Gross, C. Hernandez-Garcia, H. Huck, I. Isaev, D. Kalantaryan, M. Khojoyan, G. Kourkafas, M. Kraslinikov, D. Malyutin, D. Melkumyan, A. Oppelt, M. Otevrel, Y. Renier, T. Rublack, F. Stephan, G. Vashchenko, Q. Zhao, I. Hartl, S. Schreiber, A. Andrianov, E. Gacheva, E. Khazanov, S. Mironov, A. Poteomkin, V. Zelenogorsky, O. Lishilin, G. Pathak, "New Ellipsoidal Laser at the upgraded PITZ Facility", Proceedings of the 37th International Free Electron Laser Conference, Daejeon, Korea, 2015, TUP034.

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[15]] T. Rublack, J. Good, M. Khojoyan,M. Krasilnikov, F. Stephan DESY, Zeuthen, Germany; I. Hartl, S. Schreiber, DESY, Hamburg, Germany; A. Andrianov, E. Gacheva, E. Khazanov, S. Mironov, A. Potemkin, V.V. Zelenogorskii, E. Syresin, "Production of quasi ellipsoidal laser pulses for next generation high brightness photoinjectors", NIM A, Volume 829, 2016, Pages 438–441.

[16] E.I. Gacheva, S.Yu. Mironov, A.K. Poteomkin, V.V. Zelenogorsky, A.V. Andrianov, E.A. Khazanov, M. Krasilnikov, F. Stephan, "3D ellipsoidal beam shaping in laser drivers for photoinjectors", LASER OPTICS (LO) 2016 International conference, proceedings, 2016, 7549761.

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[18] S. Yu. Mironov, A. K. Potemkin, E. I. Gacheva, A. V. Andrianov, V. V. Zelenogorskii, M. Krasilnikov, F. Stephan, and E. A. Khazanov, "Generation of 3D ellipsoidal laser beams by means of a profiled volume chirped Bragg grating" Laser Phys. Lett. 13,

055003 (2016).
[19] O. Brovko, A. Grebentsov, N. Morozov, E. Syresin, M. Yurkov, “Diagnostic technique applied for FEL electron bunches”, Physics of Particles and Nuclei Letters, 2016, Vol. 13, No. 3, pp. 384–389.
[20] C. Hernandez-Garcia, M. Krasilnikov, G. Asova, M. Bakr, P. Boonpornprasert, J. Good, M. Gross, H. Huck, I. Isaev, D. Kalantaryan, M. Khojoyan, G. Kourkafas, O. Lishilin, D. Malyutin, D. Melkumyan, A. Oppelt, M. Otevrel, G. Pathak, Y. Renier, T. Rublack, F. Stephan, G. Vashchenko, Q. Zhao, “Charge production studies from Cs2Te photocathodes in a normal conducting RF gun”, Nuclear Inst. and Methods in Physics Research, A 871 (2017) 97–104
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[22] P. Boonpornprasert, M. Krasilnikov, F. Stephan, „Calculations for a THz SASE FEL Based on the Measured Electron Beam Parameters at PITZ“, Proceedings of FEL2017, Santa Fe, USA, WEP004.
[23] J.D. Good, G. Asova, P. Boonpornprasert, Y. Chen, M. Groß, H. Huck, I.I. Isaev, D.K. Kalantaryan, M. Krasilnikov, X. Li, O. Lishilin, G. Loisch, D. Melkumyan, A. Oppelt, H.J. Qian, Y. Renier, T. Rublack, F. Stephan, A.V. Andrianov, E. Gacheva, E. Khazanov, S. Mironov, A. Poteomkin, V. Zelenogorsky, I. Hartl, S. Schreiber, E. Syresin “Preliminary On-Table and Photoelectron Results from the PITZ Quasi-Ellipsoidal Photocathode Laser System”, Proceedings of FEL2017, Santa Fe, USA, WEP006.
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[26] N.I. Balalykin, V.F. Minashkin, M.A. Nozdrin, G.D. Shirkov, V.V. Zelenogorskii, E.I. Gacheva, A.K. Poteomkin, J. Huran "Electron gun with a transmission photocathode for the Joint Institute for Nuclear Research photoinjector" Phys. Usp. 60(10) (2017); DOI: 10.3367/UFNe.2017.03.038145