Proposal for collaborative research

Timing **Mo**des for Advanced Light Sources
Acronym: **TiMo**

In the scope of the BMBF framework programme
"Erforschung von Universum und Materie - ErUM",

Call for research and development in the field
"Erforschung der Materie an Großgeräten"

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(with own subprojects and own easy AZAP/AZK proposals)

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Brief Summary / Kurzfassung der Vorhabensbeschreibung

Vorhabensbeschreibung

Die komplexen Anforderungen moderner Experimente an Synchrotronstrahlungsquellen fordern eine große Flexibilität und Variabilität in den Parametern der Strahlung und damit einhergehend eine große Flexibilität des Beschleunigers ein. Neben Brillanz sind Pulswiederholrate und Pulsdauer entscheidende Größen für Nutzergruppen, die mit spektroskopischen und zeitaufgelösten Untersuchungsmethoden dynamische Prozesse in Materie untersuchen.

Dieser Verbund bündelt die Beschleunigerexpertise speicherring-basierter Synchrotron-strahlungsquellen in Deutschland an der TU Dortmund (TUDo), am Karlsruher Institut für Technologie (KIT) und am Helmholtz-Zentrum Berlin (HZB) im Hinblick auf die Erzeugung kurzer und variabler Pulsdauern und flexibler Pulswiederholraten, um neuartige Betriebsmodi zu entwickeln und bestehende zu verbessern. Ziel ist es, die Leistungsfähigkeit und das Anwendungsspektrum aktueller Großforschungsanlagen, wie z.B. BESSY II/VSR, zu erweitern und der Nutzergemeinschaft bisher nicht dagewesene Experimentiermöglichkeiten anzubieten. Machbarkeitsstudien sollen zeigen, inwieweit die zu entwickelnden Konzepte kombinierbar sind mit aktueller Magnetoptik-Entwicklung wie dem “Multi-Bend-Achromat” (MBA), um in zukünftigen “Diffraction Limited Storage Rings” (DLSRs) zeitaufgelöste Experimente zu ermöglichen.
Der Verbund setzt sich aus fünf klar abgegrenzten Teilprojekten (TP) zusammen, die aber in der Realisierung eines Nutzerzustandes an existierenden Anlagen und im Designprozess neuer Großgeräte intensiv miteinander verflochten sind und stark ineinandergreifen:

TP A (KIT): Micro-Bunching-Kontrolle und physikalische Limits des low-α Betrieb
TP B (TUDo): Grundlagen der Transverse Resonant Island Buckets (TRIBs)
TP C (HZB): TRIBs Injektion - Injektion in eine Zwei-Orbit-Maschine
TP D (HZB): Timing-Modi wie VSR, TRIBs und low-α in DLSR
TP E (TUDo): Echo-Enabled Harmonic Generation (EEHG) für BESSY II und DLSRs

Geplante Ergebnisverwertung

Die fünf Forschungsthemen können aktuelle Nutzerbetriebsmodi von Großforschungsanlagen, wie BESSY II/VSR verbessern, neuartige Betriebsmodi einführen und der Nutzergemeinschaft bisher nicht dagewesene Experimentiermöglichkeiten ermöglichen. Das hier vorgestellte Vorhaben hat das Potential das Design zukünftiger Anlagen, wie z.B. BESSY III, unmittelbar zu beeinflussen und Lösungswege für absehbare Herausforderungen, wie Injektion und Vereinbarkeit von Timing-Modi in DLSRs, aufzeigen. Ziel des Verbundes ist es, durch ein tiefgehendes Verständnis der zugrunde liegenden physikalischen Effekte die Entwicklung der neuartigen Betriebsmodi voranzutreiben, so dass realistische Nutzerbedingungen erreicht werden.
Mögliche Ergebnisverwertung:

- Publikationen und gute Vernetzung von Nachwuchswissenschaftlern
- Optimierung des low-α-Modus bei BESSY II (TP A)
- Neue Timing-Modi für aktuelle Großforschungsanlagen BESSY II/VSR (TP A, B, C, E)
- Design-Konzepte für zukünftige Anlagen: Timing-Modi für DLSRs
  (von den MAX-IV-Nutzern angefragt; Option für BESSY III) (TP A, B, C, D, E)
- Injektionsschemata für BESSY II und DLSR (TP B, C, D)
- Etablierung eines ErUM Forschungsschwerpunktes:
  “Light Sources with highest flexibility and variability”

1. Objectives

1.1 Main Objectives of the Collaboration

Upcoming Diffraction-Limited Storage Rings (DLSRs) [bar2016], optimized mainly for one parameter only, the brilliance, will operate with long bunches and homogenous fill pattern, as has been demonstrated at MAX IV, lacking in flexibility and variability in the longitudinal phase space for spectroscopy and timing experiments [omax2018] as

- Pump-probe (require ultrashort pulses, precisely controllable delay)
- Time-of-flight (require low pulse repetition rate for time detection and resolution)
- Coincidence (require low pulse repetition rate for unambiguous assignment) [ocoe2018]
- High-intensity applications (require micro-bunched beam for coherent emission).

Therefore, besides high average brightness, the pulse length and pulse repetition rate are parameters of great interest for user groups, who investigate dynamic processes of matter and materials in addition to their static properties. The timing user community demands a large flexibility and variability in these two parameters, which in the best case are simultaneously available with a high-average-brightness radiation source [gos2018]. Thinking further, fast switching or selecting methods are needed to allow the users at the endstation to choose the best tailored radiation properties, i.e., a timing mode, for their experiment any time at will.

Large-scale facilities try to fulfill these requirements by special timing modes as low-α operation, single- or few-bunch modes, but only for a few weeks per year, i.e., not simultaneous to high average brightness, or by complex fill patterns with advanced separation schemes and short-pulse generation by slicing, coherent harmonic generation (CHG) or echo-enabled harmonic generation (EEHG). Thus timing modes involve

- Methods to generate ultrashort pulses (low-α, high-gradient (VSR), femtoslicing, EEHG)
- Methods to provide
    - Different pulse lengths simultaneously (BESSY VSR, femtoslicing, CHG, EEHG)
    - Different repetition rates simultaneously (MHz X-ray choppers, bunch separation schemes such as vertical kicking, pulse picking resonant excitation (PPRE) or transverse resonance island buckets (TRIBs)
- Methods to produce micro-bunching (self-interaction of electron bunch with coherent synchrotron radiation (CSR), laser-electron interaction)

The main objective of this collaboration “Timing Modes for Advanced Light Sources” (TiMo) is to develop new timing modes for existing user facilities, especially for BESSY II/VSR, trying to fulfill many of the user requests and stretch out these concepts towards DLSR. The three main research topics will be

1. Short-pulse generation by EEHG schemes and control of the micro-bunching instability for the optimization of short-bunch modes like low-α or VSR
2. Two orbits in one ring using TRIBs as bunch separation scheme
3. Extrapolation of these advanced timing modes to future storage-ring-based light sources and their lattice design.

If successful, the outcome of this project could change to some extent the established rules of how storage-ring-based light sources have been designed and operated for the last 50 years.

The activities will be realised in a strongly interacting collaboration between the research groups of Prof. Dr. A.-S. Müller (KIT), Prof. Dr. S. Khan (TUDo) and Dr. P. Goslawski (HZB), bringing together the expertise of timing modes in storage rings in Germany, i.e., short-pulse generation and bunch separation schemes for a wide range of repetition rates.
This collaboration is composed of five clearly demarcated subprojects (SPs), which are strongly interlinked and have to rely on each other when establishing new user modes at existing large-scale facilities or when developing the design of a future facility:
SP A (KIT): Micro-Bunching Control and Physical Limits of low-α Operation
SP B (TUDo): Fundamental Studies of Transverse Resonant Island Buckets (TRIBs)
SP C (HZB): TRIBs Injection - Injection into a Two-Orbit Machine
SP D (HZB): Timing-Modes such as VSR, TRIBs and low-α in DLSRs
SP E (TUDo): Echo-Enabled Harmonic Generation (EEHG) for BESSY II and DLSRs

The team at KIT will further study the longitudinal dynamics underlying the **micro-bunching** instability, induced by self-interaction with emitted CSR, explicitly aiming at feasible **control** of the phenomenon. These efforts are supported by the recent in-house development of the simulation code Inovesa and can be tested in the already established low-α operation mode at the KIT storage ring KARA and also at BESSY II and MLS. The fast, synchronised sensor network at KARA allows for turn-by-turn diagnostics and thus provides ideal conditions for establishing a machine learning based longitudinal feedback acting on the micro-bunching instability. Additionally, the complex diagnostics will facilitate tests to establish new injection optics for direct and continuous injection into the low-α lattice. In combination with studies for the aforementioned feedback, this will yield a more fundamental understanding of the longitudinal dynamics and **explore the physical limits** when aiming for low-α optics or VSR scheme as user operation mode [abo2003, vsr2015].
At HZB, '**Two Orbits with TRIBs'** will be further developed towards a realistic user operation mode. During the last funding period from 2016 to 2019 within the collaboration "Messplatz mit angepasster Zeitstruktur für Spinfilter-Impulsmikroskop, 05K16CBB", many proof-of-principle and pioneering experiments with beamline scientists, in-house and external users have demonstrated the feasibility and meaningfulness of this operation mode and revealed the last big threshold towards a realistic user operation mode - the **TRIBs injection process**. This collaboration aims at overcoming this last threshold in order to establish this setting as new timing mode at BESSY II.
The TU Dortmund with the storage ring DELTA will investigate the beam dynamics in the non-linear regime using transverse resonances in greater detail and broader range than would be possible at BESSY II. The accessibility of DELTA allows for more **basic studies of TRIBs** in contrast to BESSY II's focus toward user operation, so that on the long term perspective many improvements for a TRIBs user mode are expected. There are a lot of open questions to investigate. The expertise of laser-induced energy modulation at DELTA will allow to develop an **EEHG concept for BESSY II** and stretch this out towards DLSRs.
The developed methods from the last funding period and the knowledge growth of this collaboration will be stretched out to current lattice developments of storage-ring-based synchrotron light sources. We want to set the starting point to combine **DLSR lattices with timing modes like TRIBs, VSR, low-α and concepts like EEHG** reaching out towards the BESSY II successor BESSY III.

1.2 Relationship to the Program Funding Objectives ‘Förderpolitische Ziele’

The goals presented in Sec.1.1 aim to strengthen BESSY II’s world wide leading position providing best conditions for spectroscopy and the timing user community. The **micro-bunching control** could directly enhance the low-α performance of BESSY II as well as the BESSY VSR parameter space. A concept for **EEHG for BESSY II** will push towards shortest pulses with high intensity, over performing femtoslicing by orders of magnitude. **Two Orbits with TRIBs** as operation mode will extend the timing capabilities of the radiation source. Instead of few weeks per year in single-bunch or few-bunch mode, the timing user community could conduct their experiments in parallel. First requests from the SPEEM beamline asked for fast switching between multibunch fill with 500 MHz repetition rate to a single- or few-bunch signal with 1.25 MHz, 5 MHz or 10 MHz repetition rate [gos2018]. TRIBs could be further investigated as bunch separation scheme for the short and long bunches of BESSY VSR, e.g., as upgrade option [vsr2015].
This collaboration aims at extending the current spectrum of applications at BESSY II/VSR by novel accelerator physics concepts and enhancing its performance. Furthermore, the knowledge growth and operational experience could be a building block for the basis for the **design of a future large-scale facility**, such as BESSY III or others, **combining Timing Modes and MBAs lattices.**
The basis for this possible impact of university research on a large-scale facility is the here proposed supra-regional collaboration between TUDo, KIT and HZB. Already now, there are common measurement campaigns and smaller projects ongoing between these three laboratories within the scope of former projects and collaborations within the program Accelerator Research and Development (ARD, mainly Subtopic 3 “ps-fs beams”) of the Helmholtz Association. The strong interlink between the five subprojects makes meetings with common lectures and measuring campaigns necessary, educating and training young researchers at the three different institutes and large-scale facilities (BESSY II, DELTA and KARA).

Within this collaboration we will try to answer many open scientific-physical questions in the scope of doctoral theses, but many technical and operational challenges at large-scale facilities will follow, which can not be processed by the resources within the timescale of this funding period. Additionally strong collaboration is planned with two other “Verbundvorhaben”

- ACT - Advanced Computational Techniques for improving operation of light sources
- NITrOLaDy - Non-Invasive Transverse beam Observation with Large Dynamic aperture.

This is the reason why we would like to propose to establish a **“ErUM-Forschungsschwerpunkt” (ErUM FSP) “Light Sources with highest flexibility and variability”**.
This proposed ErUM FSP would strengthen the role of **BESSY II/VSR** and its possible **successor BESSY III** and would establish a thematic network of excellence in Germany. Such a ErUM FSP would offer the possibility to increase the international visibility of HZB and its partners. It will allow for better networking, coordination and faster implementation and realisation of the proposed ideas. The ErUM FSP would perfectly fit with its topics to the ARD subtopic 2 “Advanced concepts & prototypes for Accelerators” and subtopic 3 “Advanced beam controls, diagnostics and dynamics” within POF IV. Due to the fact that short-pulse production is also a topic at linear accelerators and ACT applications will rise up at all Helmholtz Centers and university institutes due to Helmholtz’s DMA initiative, a ErUM FSP will allow these two collaborations to be more open by “flankierende Maßnahmen” for new participants and collaborators, e.g., by organizing open workshops or satellite meetings at ARD workshops.

1.3 Scientific & Technical Aims for the Collaboration

SP A: Micro-bunching Control and Physical Limits of low-α Operation

Above the **micro-bunching** instability threshold, the longitudinal charge distribution varies continuously due to CSR self-interaction. This suggests that an adaptive feedback is required in order to establish extensive control over the longitudinal beam properties. Moreover, the highly non-linear dynamics render designing such a feedback system a particularly ambitious task. One promising approach to solving this problem is based on methods of adaptive control that were developed in the field of machine learning and have seen great success in various applications over the past decade [act2017]. Specifically, the evaluative feedback that is characteristic for the sub-field reinforcement learning represents a reasonable cornerstone for this application. The LAS in collaboration with the High Performance Humanoid Technologies group of Tamim Asfour in the KIT Institute for Anthropomatics and Robotics will pursue different ways of employing these methods in order to establish control of the micro-bunching instability and to optimize CSR emission. Based on the information provided by the available turn-by-turn diagnostics, the feedback will be able to act on the micro-bunching via modifications to the RF system of the storage ring. Combined with studies of the direct injection into a low-α optics, this will provide further optimization, control and understanding of the short-bunch operation at storage rings.

SP B: Fundamental Studies of TRIBs

The SP B aims at detailed theoretical investigations and extensive beam tests for TRIBs which can partially be conducted at the electron storage ring DELTA at TU Dortmund and partially at BESSY II. This will not only increase the available beamtime drastically but will also allow to study the not yet well-explored TRIBs phenomenon at different machines in different parameter regimes regarding, e.g., beam emittance and bunch length. At both storage rings, additional insight can be gained from applying laser-induced energy modulation with femtosecond laser pulses and by using bunch-by-bunch feedback systems. Theoretical and simulation studies will address the required boundary conditions for stable TRIBs operation of a storage ring, the optimization of dynamic aperture, the population of and diffusion processes between transverse island buckets (spontaneous or triggered by laser or positive feedback), as well as new user applications taking advantage of TRIBs.

SP C: TRIBs Injection - Injection into Two Orbit Machine

With decaying beam, **TRIBs** have been proven by pioneering experiments with beamline scientists and in-house users at BESSY II to be a promising bunch separation scheme, offering to some extent two radiation sources in one storage ring. The last conceptional challenge is the top-up injection into such a storage ring setting without disturbing the user signal from the standard orbit. Two approaches will be pursued to meet this challenge:

- Technical Approach: Reduce the disturbance of the injection process, which is based on the classical 4-kicker injection into the standard orbit, from now 8 seconds to below 1 second, which would be sufficient for user operation.
- Physical / Conceptual Approach: Investigate a new injection approach, based on the idea to inject directly into the 2nd TRIBs orbit without disturbing the standard orbit, e.g., by using a non-linear kicker.

While the technique of using TRIBs as bunch separation scheme has been pioneered at HZB, little beamtime is available at the dedicated user facility BESSY II for systematic studies. The main focus lies on proof-of-principle experiments to demonstrate a concept for realistic user operation.

SP D: Timing-Modes such as VSR, TRIBs and low-α in DLSRs

The SP D will be strongly interlinked with all other subprojects and aims at developing rules and concepts of how to design a lattice optimized for timing modes combined with low emittance. The starting point will be a careful analysis of current state-of-the-art MBA lattices with respect to longitudinal beam dynamics parameters. Single-particle beam dynamics studies will evaluate fundamental bunch length limitations, which can be realised or explored in a low-α low-emittance lattice (with SP A). Furthermore, timing concepts such as VSR and TRIBs (with SP B) will be combined with the best MBA candidate in order to estimate the reachable parameter space and investigate whether TRIBs could be an injection scheme for future DLSRs (with SP C). The most promising lattice candidate will be the input for SP E. By intense communication between the different subtopics, an iterative process should be started, resulting in a best combination of low-emittance lattice optimised for timing experiments.

SP E: EEHG for BESSY II and DLSRs

Given the large number of storage-ring-based light sources serving multiple users simultaneously compared to existing high-gain FELs, it is worthwhile to explore methods extending the capabilities of storage rings regarding pulse duration and coherent emission. Among the to-date conceived short-pulse techniques for storage rings [kha2016], the application of EEHG [stu2009] promises the best compromise between ultrashort pulse duration, pulse intensity, and wavelength. EEHG has not yet been implemented at a storage ring, but was proposed, e.g., for SOLEIL [eva2012] and is already underway at DELTA [mey2017]. At DELTA, the two modulators and the radiator will be placed in one straight section. In [eva2012], on the other hand, one straight section accommodates the first modulator while a second houses the second modulator and the radiator. This scheme is better adapted to existing synchrotron light sources like BESSY II or a future DLSR, which may be BESSY III.

The goal of the SP E is to explore the conditions for EEHG at BESSY II and at DLSRs theoretically and by simulation, supplemented by experimental results seeding studies at DELTA and femtoslicing at BESSY II. Experimental studies will include CHG as well as a microwave instability triggered by laser-electron interaction. Simulations address in particular effects suppressing short-wavelength microbunching including emittance, beam dynamics, incoherent and coherent synchrotron radiation, space charge and other collective phenomena.

A concept of a future large-scale facility will be worked out combining the properties of a DLSR with an EEHG-based short-pulse source. Such a facility may even be a "pump-probe factory", i.e., a storage ring in which ultrashort-pulse generation is the central feature. Within the scope of this forward-looking project, the partners will also explore the possibilities of storage rings featuring steady-state microbunching.

2. State of the Art Science & Technology; Previous Work & Results

With the exception of the BESSY VSR upgrade project, nearly all 3rd generation light sources focus only on the emittance and neglect entirely the longitudinal parameters of the electron beam and radiation pulses. First signs point to a slight change of this trend [omax2018, gos2018, vsr2015, vsr2013, mit2018]. Currently, BESSY II offers best measuring conditions to the timing user community only in a few weeks per year in low-α operation [abo2003] to provide short pulses (see Sec. 2.1) and in single- or few-bunch operation to adjust the repetition rate [tus2016]. In addition, some light source facilities try to include timing modes into their standard operation using a complex filling pattern of their storage ring and bunch separation techniques (see Sec.2.2) [mue2016]. So far, there is no timing mode concept for existing MBA rings [omax2018] (see Sec.2.3).

2.1 Micro-Bunching Control, Low-α Operation and CSR Instability (SP A)

State of the Art Science & Technology: The low-α setting of the magnetic lattice opened storage-ring-based synchrotron light sources for shorter pulses below 10 ps down to ~ 800 fs (rms) but with bunch current limited by the micro-bunching instability. Instead of reducing the momentum compaction factor α, shorter bunches can be generated by increasing the longitudinal focussing which will be realized at BESSY VSR [vsr2015]. Together with low-α optics, bunch lengths below 500 fs can be achieved but again with reduced current [vsr2015, gos2014]. A fast feedback acting as control of the micro-bunching instability has the potential to enable operation with stable bunch length and CSR emission also at currents above the instability threshold. This, in turn, would result in much higher CSR intensity that can be offered to user experiments at storage rings like KARA or BESSY II /VSR.

Previous Work & Results: The micro-bunching instability and the corresponding bursts of THz radiation have been extensively studied over the last years at KARA, the 2.5 GeV electron storage ring at KIT. Due to the development of fast THz detectors and read-out electronics (KAPTURE), the intensity of the emitted THz radiation can be measured turn-by-turn and bunch-by-bunch and provides valuable information about the longitudinal beam dynamics [bro2016, cas2014]. Furthermore, the KIT storage ring has an electro-optical near-field setup, that enables direct measurements of the longitudinal electron distribution [hil2013, sch2017a]. Equipped with an ultra-fast detector line array (KALYPSO), the longitudinal profiles can be measured at MHz repetition rate and provide direct diagnostics of the fluctuating charge density [rot2016]. These diagnostics have been developed in the collaboration “Neue elektronische und optische Detektorsysteme und Methoden zur Untersuchung der Dynamik hochrepetitiver kurzer Elektronenpakete - 05K16VKA” within the funding period 2016-2019. Apart from experimental studies, the longitudinal dynamics can also be simulated by numerically solving the Vlasov-Fokker-Planck equation, where the CSR self-interaction can be added as a perturbation to the Hamiltonian. Based on the approach of Warnock and Ellison [ven2005], the in-house developed simulation code Inovesa is massively parallelized and thereby enables comprehensive studies of the dynamics underlying the micro-bunching instability [sch2017b, bol2017, bol2018]. Simulations, extension of the sensor network, as well as the comparison of experiments with the underlying theory [ste2017] are crucial ingredients for future efforts towards control of the micro-bunching instability.

2.2 Two Orbits with TRIBs in One Ring; A new Bunch Separation Scheme (SP B, C)

State of the Art Science & Technology: In order to fulfill the request of the timing user community for different repetition rates, light sources offer a small amount of single- or few-bunch operation per year [tus2016]. In addition, some storage rings operate with a complex bunch filling pattern [mue2016] and provide bunch separation techniques such as vertical kicking [sun2012], MHz chopper [foe2015] and pulse picking by resonant excitation (PPRE) [hol2014] to extend the measuring time for timing users but along with trade-offs in the parameter space. Motivated by a user request [tus2016] and by beam dynamics topics of the BESSY VSR project, TRIBs become of interest as bunch separation scheme at HZB.

Previous Work & Results: In the context of the collaboration "Messplatz mit angepasster Zeitstruktur für Spinfilter-Impulsmikroskop - 05K16CBB" within the funding period 2016-2019, a few-bunch mode was tested with decaying beam for the first time at BESSY II [tus2016] and implemented with top-up injection during 2017 as fixed part in the beamtime schedule.

Already since 2015, first studies with TRIBs have been conducted at the Metrology Light Source (MLS) of the PTB (Physikalisch-Technische Bundesanstalt) resulting in a first user experiment [rie2015, ari2018]. In parallel, first studies have been realised at BESSY II, also including beamline scientists and in-house users, showing good separation of the two orbits at bending and insertion device (ID) beam lines and a very good beam stability and robustness of both orbits even when many undulators were changing gaps or switching their polarisation [gos2016], but only with decaying beam. Top-up injection into the TRIBs setting very close to the 3rd order resonance was impossible at that time. Motivated by the promising results and the positive feedback from the user community, top-up injection into TRIBs was studied and accomplished in 2017 based on the standard 4-kicker injection scheme [gos2017]. The TRIBs machine setting was investigated by measurements of tune shift with amplitude [kra2018a] and the emittance and optical functions of the 2nd orbit were determined [kra2018b]. The so far achieved results gave confidence for a whole "Two Orbit User Test Week" at BESSY II in February 2018 in order to move the setting towards realistic user operation [ogos2018]. The user feedback [gos2018] revealed, in addition to many minor, mostly technical issues, a last big challenge for a realistic user operation mode, the top-up injection process.

TRIBs operation as bunch separation scheme at BESSY II and MLS is worldwide unique and new insight into this novel scheme is expected from its application at another storage rings, for which DELTA in Dortmund is an ideal candidate given the available beamtime. In order to get a deeper understanding of resonance influence on the beam, the prospective collaboration partners started to investigate 3rd-order resonance at BESSY II (vertical) and at DELTA (vertical and horizontal) in joint machine study shifts. Not only TRIBs but also low-α was addressed in these common experiments and first attempts have been made at DELTA to set up a low-α lattice already achieving 20% bunch length reduction.

2.3 Timing modes as VSR, TRIBs, low-α and EEHG in DLSRs (SP D, E)

State of the Art Science & Technology: So far, there is no concept for timing modes such as VSR, TRIBs or low-α in DLSRs on the market. HZB with BESSY II/VSR with its user community specialised in spectroscopy and timing experiments is the place to realise it.

On the other hand, concepts to produce ultrashort pulses of below 100 fs (not low-α and not high gradient) at storage rings have been demonstrated. The concepts manipulate a short "slice" within the bunch using ultrashort laser pulses:

- Femtoslicing [zho1996] was demonstrated at ALS [sch2000] and is in user operation at BESSY II [kha2006a], SLS, and SOLEIL. It allows to produce any photon energy, but only at a very low photon rate, which limits its usability (ruling out, for example, photoemission).
- CHG [gir1984] has been successfully established at Elettra, UVSOR and DELTA [kha2013] and provides high intensity, but is limited to low harmonics of the seeding laser wavelength. So far, CHG could not attract a large user community.

- EEHG was proposed in 2009 as an FEL seeding scheme [stu2009], providing high intensity at higher harmonics compared to CHG. It has been tested without FEL gain at NLCTA at SLAC (Menlo Park, USA) [xia2010] reaching the 75th harmonic of a seed wavelength of 2400 nm [hem2016], while FEL gain up to saturation at low harmonics was demonstrated at the DUV-FEL (Shanghai, China) [zha2012].

CHG and EEHG are based on laser-induced microbunching giving rise to coherent emission. Microbunching is also produced when the current threshold of the microwave instability is exceeded. This instability has different regimes in which it can be controlled by tuning the longitudinal bucket parameters (SP A), and it can be seeded by laser-electron interaction [byr2006].

Steady-state microbunching, which would allow for FEL-like radiation emission with the high revolution frequency of a storage ring, is an active research topic [rat2010].

Previous Work & Results:

HZB develops timing concepts such as VSR or TRIBs and implements them at BESSY II (and DELTA). First discussions and studies of MBA lattices have just started and are ongoing, e.g., within a scope of a master's thesis.

Besides the pioneering EEHG experiments described above, further projects at FELs are underway at FERMI (Trieste, Italy), reporting first success this summer, and FLASH at DESY (Hamburg, Germany). To-date the ongoing project at DELTA [mey2017] is the only commitment worldwide to implementing EEHG for short-pulse generation at a storage ring. At DELTA, EEHG is going to be realised in one 20 m long straight section where two new undulators will be installed in addition to the already existing device. The common straight section is required to retain the delicate phase space pattern created by a two-fold laser-electron interaction in the first two undulators (the modulators) in order to radiate coherently at short wavelength in the third undulator (the radiator).

2.4 Previous work of the applicants

During her a CERN fellowship in 2002, the group leader at KIT-LAS (Prof. A.-S. Müller) worked on the nonlinear beam dynamics of resonant islands in transverse phase space at the CERN Proton Synchrotron [gil2006, mul2002]. In 2007 she became leader of a Helmholtz-University Young Investigator Group at KIT dedicated to the study short-bunch micro-structures and CSR emission. Those studies encompassed the development of beam diagnostics tools [hil2013], methods [bro2016] and simulation codes [sch2017b]. In a close collaboration with HZB since 2008, the characteristics CSR emitted by short bunches in storage rings (MLS and KARA) were investigated [mul2009]. Common experiments with the partner TU Dortmund, performed at DELTA, targeted the behaviour of laser-modulated bunches observed with coherent sub-terahertz radiation [mai2015].

The group leader at TU Dortmund (Prof. S. Khan) has participated in the construction and operation of BESSY II between 1993 and 2006, studying collective phenomena [kha2006b] and establishing the worldwide first femtoslicing user facility [kha2006a]. Since 2006, he participated in seeding-related studies at FLASH in Hamburg – see, e.g. [ang2008, ack2013, hac2015]. His group at TU Dortmund performs CHG studies at DELTA since 2011 [kha2013] and work on implementing EEHG at DELTA is in progress [mey2017]. At the time of writing, first attempts towards establishing TRIBs (as well as low-α) at DELTA are undertaken in collaboration with the prospective project partner from HZB.

At HZB's institute for accelerator physics, Dr. P. Goslawski, is responsible for operation and development of both storage rings BESSY II and MLS. He fills in different positions within the BESSY VSR project, e.g., editor of the conceptual design report, subproject ('VSR beam') and work package leader ('VSR beam - separation') on beam dynamics topics. He coordinates the HZB activities within the program ARD subtopic 3 "ps-fs beams" in POF III and initiated the TRIBs development at HZB and lead the project towards realistic user operation.

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3. Detailed description of the project plan

3.1 Project-related resource planning

Financing from own funds of the project partners

Personnel involved in the project financed from own funds of the project partners
Karlsruher Institute for Technology: Prof. Dr. A.-S. Müller (subproject leader), Dr. Akira Mochihashi (accelerator development and operation - KARA), Prof. Dr. Tamim Asfour (specialist for machine learning and adaptive feedback systems).
Technische Universität Dortmund: Prof. Dr. S. Khan (subproject leader), Dr. G. Schmidt (accelerator physicist), C. Mai (THz and Delta specialist).
Helmholtz-Zentrum Berlin: Prof. Dr. A. Jankowiak (subproject leader). Dr. P. Goslawski (subproject leader), Dr. M. Ries (accelerator development and operation - BESSY II), Dr. T. Mertens

(accelerator simulation and theory), Dr. J.-G. Hwang (diagnostics and beam dynamics), Dr. T. Atkinson (BESSY II injector system).

Required supplementary funding (without overhead)

All investment for hardware listed here is not part of the basic equipment of the laboratory. Mainly additional personal is needed to realise the proposed research and developments. Due to the strong thematic and experimental connection between the subprojects, common lectures & workshops, measurement campaigns and machine commissioning and development shifts are planed. Due to the fact that the travel expenses are considered for national (DPG-Frühjahrstagung) and international (e.g., IPAC, ESLS) workshops and conferences, and there is a strong interest of at least two futher collaborations on “Timing Modes for Advanced Light Sources”, we are considering to propose a “ErUM Forschungsschwerpunkt” and finance collaborative events with “flankierenden Maßnahmen”.

Institute and subproject	**Personnel**
Karlsruher Institut for Technology subproject A: Micro-Bunching Control	1 doctoral position (¾ TV-L E13 for 3 years) 3 student assistants
Technische Universität Dortmund subproject B: TRIBs Basics subproject E: EEHG for BESSY II & DLSRs	1 doctoral position (¾ TV-L E13 for 3 years) 1 doctoral position (¾ TV-L E13 for 3 years)
Helmholtz-Zentrum Berlin subproject C: TRIBs injection subproject D: Timing Modes in DLSRs	1 doctoral position (¾ TVöD E13 for 3 years) 1 doctoral position (¾ TVöD E13 for 3 years)

The subproject A will be conducted within the scope of a doctoral thesis (3/4 TV-L E13 for 3 years). Considering the already established diagnostics network, and combined with the existing simulation code developed at KIT, only a small amount of additional equipment is required. We therefore merely request 8 kEUR for storage of systematic simulations of longitudinal beam dynamics. Regarding the scope of the task, we would like to involve early career scientists (student assistants) in the development of the feedback system. They will be particularly needed for labor-intensive tasks in the processes of training and evaluation of different approaches, as well as for assistive script and software development for the purpose of interfacing with simulation and production environments.

The subproject B will be conducted within the scope of a doctoral thesis (3/4 TV-L E13 for 3 years). Given the existing diagnostics capabilities (including, e.g., a streak camera) and the possibilities of acting on the electron beam with femtosecond laser pulses and bunch-by-bunch feedback systems in all three coordinates at DELTA, the additional hardware requirements for the subproject are marginal. We request 20 kEUR for a new setup to monitor the beam spot including a digital camera, optics and the mechanical setup.

The subproject E will be conducted within the scope of a doctoral thesis (3/4 TV-L E13 for 3 years). The doctoral student will participate in ongoing experimental seeding studies at DELTA as well as at BESSY II. Simulations will be conducted with public-domain programs and self-written code. Therefore, no additional funds for hardware and software are required.

The subproject C will be conducted within the scope of a doctoral thesis (3/4 TVöD E13 for 3 years). The doctoral student will participate in both theoretical and experimental ongoing TRIBs studies at BESSY II, MLS and DELTA. A close cooperation with the injector group is necessary to investigate the injection into BESSY II. The main working topics are to reduce the disturbance on the main orbit when injecting in TRIBs and to develop an injection procedure directly into the TRIBs orbit and estimate whether it is applicable at BESSY II and stretch it out to an MBA lattice. A candidate with strong experimental background is required for realising physical concepts using complex advanced technical setups, like a non-linear kicker or bunch-by-bunch feedback systems.
The subproject D will be conducted within the scope of a doctoral thesis (3/4 TVöD E13 for 3 years). The position is foreseen for a candidate who already has a basic understanding of lattice development, design and its implementation in a real machine. A very good fitting candidate would be Felix Andreas, who developed and tested a lattice modification with his own code for BESSY VSR in BESSY II within his bachelor's thesis. In his Master thesis, he will continue this work, include non-linear beam dynamics and start to investigate MBA achromat lattices. Felix Andreas would be an enrichment for HZB's beam dynamic group.

3.2 Milestone planning and project bar chart

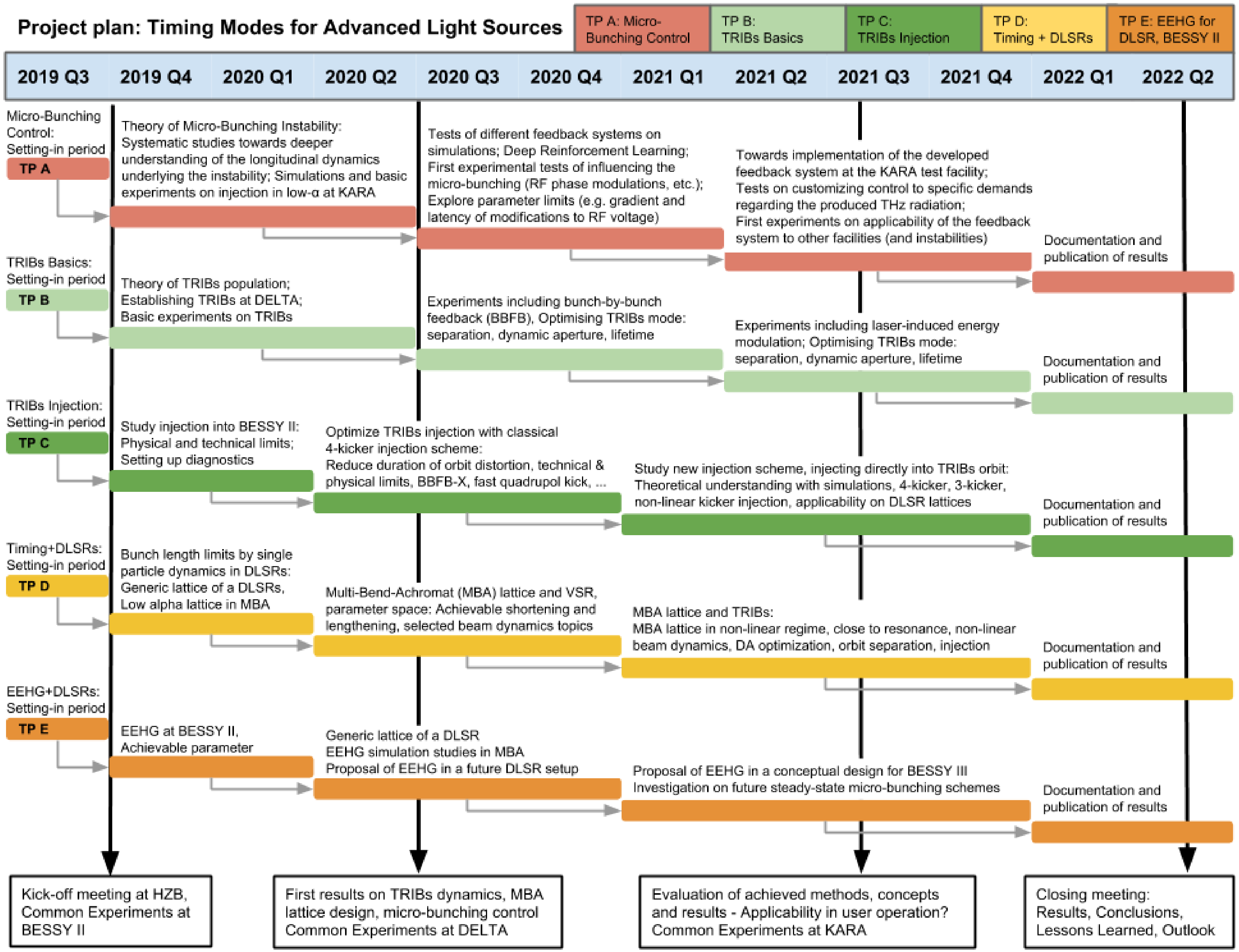
The work packages of the individual subprojects are described in following list and figure. A number of envisaged milestones common to several subprojects could be, e.g.,

- First test of micro-bunching control at KARA
- Establishing TRIBs setting at another machine such as DELTA or KARA
- Implementation of TRIBs optimisation at one of the three rings due to better beam dynamics understanding
- Direct injection into TRIBs orbit
- First EEHG experimental tests at DELTA and laser-electron interaction at BESSY II
- Election of best MBA lattice for timing modes

However, to avoid confusion, only four symbolic milestones for common measurements at the three facilities are defined within the figure, but, more joint activities already ongoing. It is foreseen that all subprojects will participate in common machine studies at BESSY II, DELTA and KARA.

SP A (KIT) work packages: Micro-Bunching Control

1.) systematic studies towards deeper understanding of the longitudinal dynamics underlying the instability to refine the approach to micro-bunching control;
2.) simulations of a 0.5 GeV low-α lattice and basic experiments on the injection at KARA;
3.) tests of possible feedback systems on simulations with focus on deep reinforcement learning;
4.) first experimental test to influence the micro-bunching instability by e.g. RF phase and amplitude modulations;
5.) exploration of physical parameter limits, e.g. gradient and latency of modifications to RF voltage;
6.) towards implementation of developed feedback system at the KARA test facility;
7.) tests on customising control to specific demands regarding the produced THz radiation;
8.) if time permits, explore applicability of the feedback system to other facilities (and instabilities);
9.) documentation and publication of results



Project plan: Timing Modes for Advanced Light Sources
TP A: Micro-Bunching Control
TP B: TRIBs Basics
TP C: TRIBs Injection
TP D: Timing + DLSRs
TP E: EEHG for DLSR, BESSY II
2019 Q3
2019 Q4
2020 Q1
2020 Q2
2020 Q3
2020 Q4
2021 Q1
2021 Q2
2021 Q3
2021 Q4
2022 Q1
2022 Q2
Micro-Bunching Control: Setting-in period
TP A
Theory of Micro-Bunching Instability: Systematic studies towards deeper understanding of the longitudinal dynamics underlying the instability; Simulations and basic experiments on injection in low-α at KARA
Tests of different feedback systems on simulations; Deep Reinforcement Learning; First experimental tests of influencing the micro-bunching (RF phase modulations, etc.); Explore parameter limits (e.g. gradient and latency of modifications to RF voltage)
Towards implementation of the developed feedback system at the KARA test facility; Tests on customizing control to specific demands regarding the produced THz radiation; First experiments on applicability of the feedback system to other facilities (and instabilities)
Documentation and publication of results
TRIBs Basics: Setting-in period
TP B
Theory of TRIBs population; Establishing TRIBs at DELTA; Basic experiments on TRIBs
Experiments including bunch-by-bunch feedback (BBFB), Optimising TRIBs mode: separation, dynamic aperture, lifetime
Experiments including laser-induced energy modulation; Optimising TRIBs mode: separation, dynamic aperture, lifetime
Documentation and publication of results
TRIBs Injection: Setting-in period
TP C
Study injection into BESSY II: Physical and technical limits; Setting up diagnostics
Optimize TRIBs injection with classical 4-kicker injection scheme: Reduce duration of orbit distortion, technical & physical limits, BBFB-X, fast quadrupol kick, ...
Study new injection scheme, injecting directly into TRIBs orbit: Theoretical understanding with simulations, 4-kicker, 3-kicker, non-linear kicker injection, applicability on DLSR lattices
Documentation and publication of results
Timing+DLSRs: Setting-in period
TP D
Bunch length limits by single particle dynamics in DLSRs: Generic lattice of a DLSRs, Low alpha lattice in MBA
Multi-Bend-Achromat (MBA) lattice and VSR, parameter space: Achievable shortening and lengthening, selected beam dynamics topics
MBA lattice and TRIBs: MBA lattice in non-linear regime, close to resonance, non-linear beam dynamics, DA optimization, orbit separation, injection
Documentation and publication of results
EEHG+DLSRs: Setting-in period
TP E
EEHG at BESSY II, Achievable parameter
Generic lattice of a DLSR
EEHG simulation studies in MBA
Proposal of EEHG in a future DLSR setup
Proposal of EEHG in a conceptual design for BESSY III
Investigation on future steady-state micro-bunching schemes
Documentation and publication of results
Kick-off meeting at HZB, Common Experiments at BESSY II
First results on TRIBs dynamics, MBA lattice design, micro-bunching control Common Experiments at DELTA
Evaluation of achieved methods, concepts and results - Applicability in user operation? Common Experiments at KARA
Closing meeting: Results, Conclusions, Lessons Learned, Outlook

SP B (TUDo) work packages: Fundamental Studies of TRIBs

1.) establishing TRIBs at DELTA;
2.) theory and methods of TRIBs populations dynamics;
3.) basic experiments and simulations on TRIBs, optimising separation and dynamic aperture;
4.) experiments including bunch-by-bunch feedback systems (BBFB);
5.) experiments including laser-induced energy modulation;
6.) documentation and publication of results

SP C (HZB) work packages: TRIBs Injection - Injection into a Two-Orbit Machine

1.) study physical and technical limits of injection into BESSY II, setting up diagnostic;
2.) optimize TRIBs injection with established classical 4-kicker scheme, reduce duration of main orbit distortion and evaluate technical and physical limits for successful top-up injection;
3a.) study new injection scheme, injecting directly into TRIBs orbit; evaluation theoretical and experimental different techniques as 4-kicker, 3-kicker and non-linear kicker injection
3b.) applicability to DLSR lattices
4.) documentation and publication of results

SP D (HZB) work packages: Timing-Mods such as VSR, TRIBs and low-α in DLSRs

1.) generic lattice of DLSRs;
2.) bunch length limits by single-particle dynamics in DLSRs, low-α lattice in MBAs;
3.) MBA lattice and VSR, achievable shortening and lengthening, selected beam dynamics topics;
4.) MBA lattice and TRIBs, MBA in non-linear beam dynamics regime, close to resonance, dynamic aperture optimisation, orbit separation, injection;
5.) documentation and publication of results

SP E (TUDo) work packages: EEHG for BESSY II and DLSRs

1.) EEHG simulation studies, EEHG concept within BESSY II DBA lattice;
2.) generic lattice of a DLSR;
3.) proposal of EEHG for a future DLSR setup and in a conceptual design for BESSY III;
4.) results on future steady-state micro-bunching schemes;
5.) documentation and publication of results

4. Utilisation plan

4.1 Prospects for commercial success

No particular commercial interest is foreseen yet, but patents could be possible.

4.2 Prospects for scientific and technological success

If the proposed concepts could be established in successful user operation, they will open new opportunities for the spectroscopy and timing user community and will enhance the efficiency and applicability spectrum. Publications and conference contributions are expected. The possibility that other laboratories (e.g. MAX IV) will be interested in these concepts is very high as proven by the consideration of a VSR scheme for other machines (e.g. SOLEIL). An EEHG facility would be an unique tool to produce ultrashort radiation pulses in storage rings and a micro-bunching control would increase the current stored in short bunches. A common project with MAX IV, e.g., on TRIBs, could be foreseen in order to get deeper insight into how to operate and design a DLSR and if the non-linear beam dynamics allow for TRIBs operation (maybe within a scope of a Röntgen Angström Cluster project?). If the concepts are successful in user operation, it is expected that further requests and stimuli will follow from the user community.

4.3 Prospects for scientific and commercial follow-up projects

As already mentioned in Sec.1.1 and Sec.1.2, this collaboration has to be seen as starting point, for a research program focusing on “Timing modes for advanced storage ring-based light sources”. The main objective is to set up pioneering experiments for the novel concepts and test their implementation under real user conditions at BESSY II/VSR and also at DELTA and KARA. However, developing new operation modi at an existing facility besides its normal user operation is associated with great effort and restricted to the annual operational schedule. The TRIBs development allow for an extrapolation and so far it was not yet studied what lattice hardware modifications have to be done to improve this non-linear operational mode.
The biggest follow-up project could be the start of the design process of a BESSY II successor. The research of this collaboration could have massive impact on such design processes and could contribute to conceptual design studies and reports.
Moreover, we considering to establish a ErUM-Forschungsschwerpunkt with two other collaborative projects ‘ACT & NITrOLaDy’ (see Sec1.2) in order to establish a solid platform for the long term perspective of this research. The objective is to establish a thematic network of excellence for **“Light Sources with highest flexibility and variability”** in Germany, which would contribute to HZ ARD programm and DMA initiative and would perfectly fit in POF IV.

5. Cooperation with third parties

Intense networking is foreseen with the proposed collaboration projects ACT und NITrOLaDy independent of an “ErUM Forschungsschwerpunkt”. Further cooperation is foreseen with HZB in-house users as well as external users (colleagues from former Spin-TOF project - 05K16CBB) and beamline scientists, with the PTB as important BESSY II user and the PTB’s MLS team within the scope of non-linear beam dynamics and their steady-state micro-bunching project.

6. Necessity of the grant

The proposed project has the potential to affect massively the current mainstream direction of upgrading 3rd generation storage-ring-bases light sources towards DLSRs, optimized only towards one parameter. It is a massive extension of the current BESSY II/VSR operation modes and will enable new opportunities for the user community. The challenging physics concepts require a intense collaborative research, which has to allow for experience and knowledge increase at different storage-ring laboratories. This all can only be realised within a “Verbundforschungsvorhaben”. After detailed research, we have not found any appropriate funding opportunity from European Union (EU) programs.

HZB Helmholtz Zentrum Berlin

Stellungnahme

des Helmholtz-Zentrums Berlin für Materialien und Energie zum

Vorhaben zur Forschung und Entwicklung
auf dem Gebiet „Erforschung kondensierter Materie an Großgeräten"

Titel: **Timing Modes for Advanced Light Sources**

Antragsteller: **Prof. Dr. Anke-Susanne Müller, Karlsruher Institut für Technologie**
Prof. Dr. Shaukat Khan, Technische Universität Dortmund
Dr. Paul Goslawski, Helmholtz-Zentrum Berlin für Materialien und Energie

Das Verbundvorhaben zielt mit den Teilprojekten 'Micro-Bunching Control' & 'Two Orbit Beam Separation using TRIBs' und 'EEHG for BESSY II and DLSRs' auf innovative Beiträge zur Weiterentwicklung der Synchrotronstrahlungsquelle BESSY II ab und eröffnet Möglichkeiten zur Entwicklung von Ausbauoptionen für BESSY VSR. Die zu erforschenden Beschleunigerphysik-Konzepte haben das Potential, die seit 50 Jahren etablierten Vorstellungen zum Betrieb und Design von Synchrotronlichtquellen zu ändern und die Verfügbarkeit von Timingmoden simultan zum Betrieb bei hoher mittlerer Brillanz zu etablieren. Diese neuen Möglichkeiten könnten auch einen zentralen Baustein für die Nachfolgequelle BESSY III definieren.

Das Helmholtz-Zentrum Berlin unterstützt den Antrag nachdrücklich und wird die zur Durchführung notwendige Experimentierzeit in "Maschinen- und Beamline-Commissioning-Zeiten" zur Verfügung stellen. In Abhängigkeit vom Reifegrad des Nutzerzustandes wird angestrebt dedizierte TRIBs Wochen in den jährlichen Strahlzeitplan einzugliedern und gemeinsame Experimente zur Exploration der Möglichkeiten dieser neuen Betriebsmodi mit der Nutzerschaft zu initiieren.

Berlin, 22.10.2018

Prof. Dr. Bernd Rech
Wissenschaftlicher Geschäftsführer (komm.)

Thomas Frederking
Kaufmännischer Geschäftsführer