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BESSY III & MLS II - STATUS OF THE DEVELOPMENT OF THE NEW PHOTON SCIENCE FACILITY IN BERLIN

P. Goslawski*, K. Holldack, A. Jankowiak, J. Lüning, A. Meseck, M. Sauerborn, J. Viefhaus, M. Abo-Bakr, F. Andreas, M. Arlandoo, J. Bengtsson, V. Dürr, J. G. Hwang, B. Kuske, J. Li, A. Matveenko, T. Mertens, E. Rial, M. Ries, A. Schälicke, M. Scheer P. Schnizer, L. Shi
Helmholtz-Zentrum Berlin, BESSY, Berlin, Germany

Abstract

HZB operates and develops two synchrotron radiation sources at Berlin Adlershof. The larger one, BESSY II with an energy of 1.7 GeV and 240 m circumference is optimized for soft-X rays and in operation since 1999. The smaller one is the MLS (Metrology Light Source), owned by the Physikalische Technische Bundesanstalt (PTB) - Germany's National Metrology Institute. It is designed to fulfill the special metrology needs of the PTB with an energy of 0.6 GeV and 48 m circumference, covering the spectral range from THz and IR to EUV/VUV. In 2020 a discussion process has been started to define the requirements for successors of BESSY II and MLS and to study the possibilities integrate them into a new photon science facility in Berlin Adlershof. Here, we give a status report and present a first envisaged parameter space to both machines (see also [1–4]).

STARTING POINT & PRECONDITIONS

The discussion on a BESSY II successor, BESSY III, started in 2020 with five basic conditions, shaping the direction of the new facility concept and storage ring layout:

1. Greenfield design on the WISTA Berlin-Adlershof
2. Diffraction limited at 1 keV photon energy
3. The 1st undulator harmonic up to 1 keV photon energy
4. Strong supporting laboratory infrastructure
5. Fulfilling the metrology requirements of PTB as a main partner and user.

Despite being the largest science and technology park in Germany, the 30 years of development of WISTA campus Berlin-Adlershof since the reunification of Germany has left only a few undeveloped sites available to house a new light source facility. This defines the **circumference of a new facility to be about 300 m**. As BESSY II has always been one of the basic building blocks of the scientific ecosystem of WISTA campus Berlin-Adlershof, it would be best for a future facility concept to stay embedded in this environment. Currently investigations of different site options are ongoing, mostly focusing on ground stability and environmental electromagnetic noise.

Science Cases and User Demands

Shortly after starting the dialogue about the BESSY III facility in classical face-to-face meetings, the corona pandemic interfered and moved the discussion to a virtual environment with the big advantage of bringing together people from all over the world, quickly and easily. Within the short time of one year, 13 Science Expert Groups workshops had been held, defining the requirements and user needs on a future BESSY III facility. All workshops have been grouped into so called main four scientific focus areas:

- Energy & Catalysis,
- Quantum & Information,
- Health & Life and
- Materials & Metrology,

indicating the main fields of scientific and technological impact of the facility.

The conclusions of the workshops and the demands on radiation properties are summed up in Fig. 1. The core photon energy range will be from 0.1 keV to 3 keV, but there are also requests starting from 10 eV and reaching up to 10 keV or even a few 10 keV. The 2nd and 3rd basic condition was strongly supported by the Scientific Experts Groups pointing out their importance of research with resonant excitation of, e.g., transition- and rare earth elements for information technology at around 1 keV. Only a 4th generation diffraction limited radiation source can fulfill the requests for radiation properties such as high spatial coherence, brilliance and smallest spot sizes. Across all groups there is a strong request

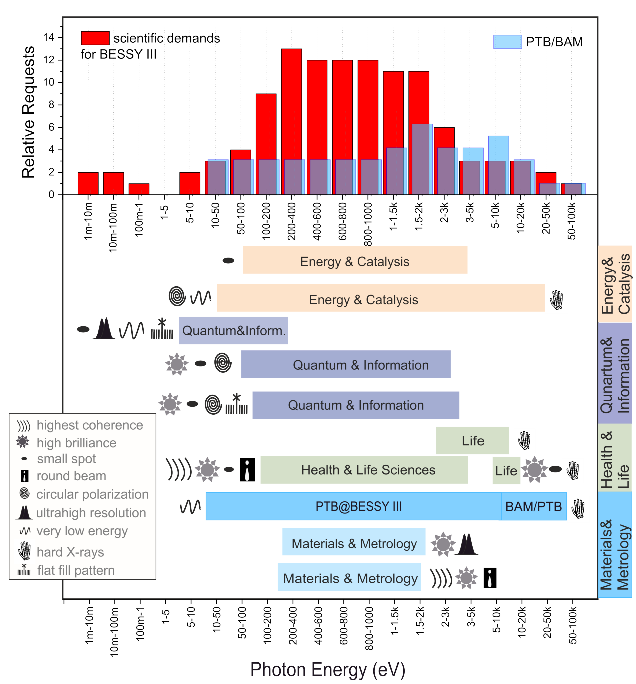

Figure 1: Main demands and requirements on BESSY III.

* paul.goslawski@helmholtz-berlin.de

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on multimodal experimental options, which include state-of-the-art and easy accessible synchrotron instrumentation combined with correlative off-line (lab) methods, complex on site material synthesis, and accelerated data processing in one integrated research facility. A first step towards such an infrastructure has been already realized at BESSY II with EMIL - the **E**nergy **M**aterials **I**n-Situ **L**aboratory [5] and will be further developed within the concept of the four scientific focus areas at BESSY III. For example, the recently funded **Cat**alysis **Lab**oratory platform CatLab [6], intended to advance the development of novel catalyst materials. These materials are urgently needed, particularly for the production of green hydrogen for the energy transition, and CatLab will be an important building block of the Energy and Catalysis cluster.

Choice of Energy and Envisaged Emittance

For diffraction limited Gaussian beams, the electron beam emittance ε_e has to be of the order as the photon beam emittance ε_r, defined by the photon wavelength $\varepsilon_e \leq \varepsilon_r \leq \lambda/4\pi$. For radiation energies up to 1 keV ($\lambda = 1.24$ nm), this requires an **electron beam emittance of about 100 pm rad**.

The request of reaching 1 keV photon energy with the 1st undulator harmonic defines the undulator period λ_U and the beam energy γ. The radiation wavelength λ_n of an undulator harmonic n on axis is given by

$$\lambda_n = \frac{\lambda_U}{2\gamma^2}\frac{1}{n}\left(1+\frac{K_n^2}{2}\right) \quad (1)$$

with the deflection parameter K, defined by the field strength (gap at permanent magnet undulators) and period length of the insertion device (ID). At BESSY II the deflection parameter for most undulators ranges from 0.8 to 4. The combination of undulator period and electron beam energy that allow for achieving 1 keV photon energy on the 1st harmonic with different K values, is shown in Fig. 2.

It becomes obvious that for beam energies below 2 GeV, a period length of ~ 20 mm is necessary to reach 1 keV. Such small period lengths would require an in-vacuum undulator solution, either at room temperature or at cryogenic temperatures. Above 2 GeV, the 1 keV becomes also accessible with out-of-vacuum undulators. The horizontal dark green band indicate the standard period length of the APPLE II undulators used at BESSY II. Choosing undulators with period length of 40 mm as main radiation sources, an electron beam energy of 2.5 GeV would be required.

Due to the importance of spectroscopic techniques, especially for a soft-X-ray facility, the tuneable radiation from the tunable gap undulators should guarantee a spectral range without dark gaps. This is fulfilled by overlapping the radiation from 1st and 3rd harmonics, see Eq. (1): $\lambda_1 = \lambda_3$ results in

$$K_{3,\max} \geq \sqrt{4 + 3K_{1,\min}^2}\,.$$

With a minimum deflection parameter $K_{1,\min} = 0.8$, this requires $K_{3,\max} \approx 2.4$, defining the minimum gap needed, depending on the period length. For classical neodymium-iron permanent magnet undulators [7] the approximate gaps required for continuous spectral range are listed in Table 1.

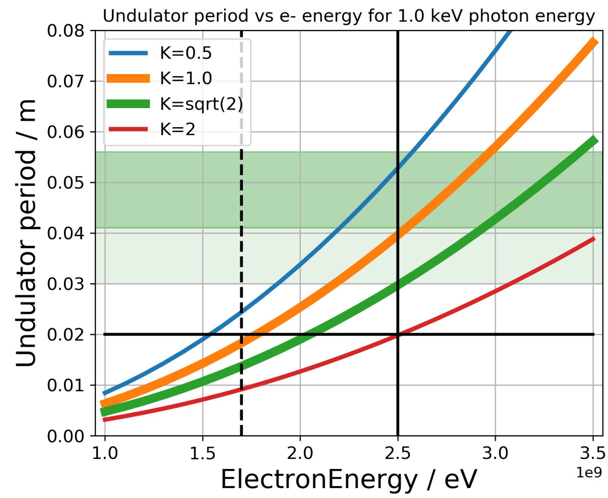

Figure 2: The choice of the beam energy depending on the undulator period selection for different K. Main period length of APPLE II used at BESSY II are indicated with the dark green area and could be extended towards the light green area by closing the gap to minimum values of 9 mm.

Table 1: Minimum Required Approximate Gap To Overlap 1st & 3rd Harmonics for Neodymium-Iron Permanent Magnet Undulators

Period length in mm	40	35	30	25	20
Required gap in mm	14.9	11.9	9.0	6.5	4.1

Minimum gaps at BESSY II are 15 mm, but could be decreased for BESSY III down to 12 mm for out-of-vacuum undulators (light green area in Fig. 2 as it has been demonstrated at MAX IV.

BESSY II's user community requests variable tunable polarization (7 of 12 undulators are elliptical APPLE II (UE)) and this request also strongly holds for BESSY III. To fulfill this request with well mature out-of-vacuum UE devices the **electron beam energy needs to be 2.5 GeV**. Currently, the development of an in-vacuum elliptical APPLE II (IVUE) is ongoing and operation will start within the next years [8]. Having proven its standard user operation capabilities, such devices will have the potential to widen the spectral range and increase the brightness of BESSY III even further.

First Boundary Conditions for MLS II

Not covered by the BESSY III facility will be the request for radiation from 1 meV to 1 000 meV, see Fig. 1, originated by the low α operation at BESSY II for the generation of coherent THz radiation and Infrared (IR) radiation. Since the integration of timing capabilities at BESSY III would need compromises on emittance and spot size, a comple-

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mentary machine concept of MLS II will preserve these experimental techniques. This has been proposed by the PTB as integrated part of a Berlin Photon Science facility, in analogy to MAX IV. The main parameters for MLS II are listed in Table 2. The MLS II will be based on the MLS [9] design, the first electron storage ring optimized to control the longitudinal phase space, which just recently allowed for a first experimental demonstration of steady-state micro-bunching (SSMB) [10]. The MLS II lattice design work started and is described here [1] in detail.

Table 2: Main Parameters of MLS and MLS II

Parameter	MLS	MLS II
Energy	0.6 GeV	0.8 − 1.2 GeV
Circumference	48 m	~100 m
# of straights	4 (2x2.5 m, 2x6 m)	6-8 with 5 m
Emittance	100 nm rad	small

First Boundary Conditions for BESSY III

Table 3 lists the main parameters of BESSY III. In order to keep the beamline capacity, and to allow for EMIL-like laboratories, the number of straights should not decrease and its length have been set to 5.6 m, to allow for ID installations of up to 5 m.

Table 3: Main Parameters of BESSY II and BESSY III

Parameter	BESSY II	BESSY III
Energy	1.7 GeV	2.5 GeV
Circumference	240 m	~300 m
# of straights	16 with 5.0 m	≥ 16 with 5.6 m
Emittance	5 nm rad	100 pm rad

BESSY III LATTICE DEVELOPMENT AND TECHNICAL REALIZATION

Based on parameters given in Table 3, first lattices have been developed and studied. A 16-period 9MBA candidate based on the ALS-U design and a 20-period 5MBA solution indicate the challenging boundary conditions listed in Table 3 when aiming for 100 pm rad equilibrium emittance. The resulting magnet specifications were too ambitious, and the decision has been made to follow a more conservative ansatz. Within the CDR phase, magnet strengths of already realized magnets will be used, e.g., conventional state-of-the-art iron yoke electromagnet technology for multipoles. An inner vacuum pipe diameter of 18 mm, guarantees good pumping capabilities, thermal load distribution and a reasonable impedance budget, defines the minimum bore diameter of 25 mm of the multipole magnets allowing for sufficiently field strength. The CDR magnet specifications have not been driven to technical limits, and are listed in Table 4. It will be upon the subsequent TDR phase to assess the technical risks and redefine the technical ambitions.

Table 4: Magnet Specifications

Magnet type	Max. Value
homogeneous dipole magnet	< 1.3 T
combined fct. bend (2 pole)	< 0.8 T and 15 T/m
combined fct. bend (4 pole)	< 0.8 T and 30 T/m
quadrupole	< 65 T/m
(used as reverse bend, too)	
sextupole	< 4 000 T/m
minimum spacing between magnets	0.1 m

A detailed analysis of the basic building blocks of a MBA structure, i.e., the magnetic components of unit cell and matching cell [2] together with the implementation of a Higher-Order-Achromat (HOA) for a robust lattice design [3], pushes forward towards a 1st baseline BESSY III 6MBA lattice. This lattice fulfills all boundary conditions with respect to ring dimensions and emittance, and is also tuned with respect to nonlinear properties. An additional, collaborative study between HZB and NSRL (Hefei) independently points towards a 6MBA solution as well [4].

The potential of a round beam is analyzed and discussed. A strongly coupled machine is improving brilliance, coherence and the electron beam lifetime but can complicate the injection process. At this state of the discussion a moderate coupling together with optimally matched Twiss parameters in the straight section are requested. The latter is achieved by setting $\beta_{x,y} = L_U/\pi$, resulting in $\beta_{x,y}$ =1.6 m for an undulator of about L_U = 5 m length [11]. To relax the lattice requirements a deviation from the optimal value by a factor 2 is accepted.

Further constraints set potential limits on the achievable emittance and define challenges in the lattice design. E.g. the PTB has to provide a primary radiation standard, i.e., an absolute, predictable and traceable radiation source for metrology purposes. For that the deflecting, magnetic field around the source point has to be known to highest precision. As the measurement sensor itself has certain spatial dimensions, a purely homogeneous dipole magnet needs to be included in the lattice. Additionally, owing to capacity reasons, at least one bending magnet source within the MBA cell is requested. Furthermore, the lattice design process should take into account the possibility of Transverse Resonance Island Buckets - TRIBs - operation with two arbitrary filled orbits and unprecedented radiation properties [12–14].

SUMMARY AND CONCLUSIONS

The discussion about a BESSY II successor started in 2020. Through 13 workshops the future science at BESSY III has been discussed, specifying the demands on the radiation source. PTB proposes to include the successor of the MLS into the project, integrating both machines into a new photon science facility in Berlin-Adlershof. The discussion and the lattice design process accelerates towards full swing.

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