B*ERL*inPro - A PROTOTYPE ERL FOR FUTURE SYNCHROTRON LIGHT SOURCES

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Abstract

The HZB (previously BESSY) was the first institution in Germany to build and operate a dedicated synchrotron light source (BESSY I). About 10 years ago BESSY-II, a third generation synchrotron light source, was commissioned. Presently, HZB is developing a design for a future multi-user light source as a successor to BESSY II and to enable "next-generation" experiments. Such a facility will be based on the energy-recovery-linac (ERL) principle. Although ERL facilities exist for the IR and THz range [1],[2] their moderate parameters (current, emittance, energy) are insufficient for x-ray sources. HZB is therefore proposing to build a prototype ERL facility (B*ERL*inPro) that will demonstrate high current and low emittance operation at 100 MeV. B*ERL*inPro is intented to bring ERL technology to maturity so that it can be employed for x-ray light sources. This paper presents an overview of the project and the key components of the facility.

GOALS OF B*ERL*inPro: ADDRESSING THE CHALLENGES OF ERLS

ERL specific issues revolve primarily around the fact that an ultra-low-emittance beam must be generated at storage-ring-level currents that then is accelerated to full energy without emittance dilution. It must also be demonstrated that efficient energy recovery is possible, even when the beam's energy spread is increased. Nearly all components along the linac are impacted by these unique operating conditions. While not all aspects can be covered exhaustively, the following are key areas which the B*ERL*inPro program will concentrate on.

Beam Dynamics

One of the ERL's advantages is the fact that emittance and bunch length do not arise from an equilibrium condition like in storage rings but are defined by the source and by bunch manipulation techniques. Therefore the challenge is to generate, accelerate and transport an electron beam of ultra high density from the source through the accelerator to the x-ray generating insertion devices.

Emittance Compensation and Preservation: an emittance compensation scheme for the entire injection path, from the gun through the booster to the entrance of the linac, has to be developed. The scheme must optimize the gun field and phase, the strength and position of the gun solenoid as well as the postion and gradient of the booster module, and consider the merger section into the main linac. Especially the merger with several dipole bends is challenging, because the emittance compensation is not yet complete. The dipoles manipulate the phase space of the low energy beam, leading to effects that can be detrimental to the emittance. Many of these issues must be revisited in studying the return arc of the ERL. Although the energy is higher, reducing the space-charge effects, coherent synchrotron radiation gains in importance due to the stronger dipoles. The return arc must also include the possibility of bunch compression and compensation of non-linearities that the bunch incurs in the main linac due to the curvature of the RF voltage. A number of theoretical concepts have already been studied in existing facilities such as the JLAB ERL-FEL [1]. However, here the emittance is at least a factor 10 higher and the current a factor 10 lower than needed for X-ray ERLs, so that effects at the sub-micron emittance level are not visible.

Bunch Length: one of the great strengths of an ERL is the high degree of flexibility with respect to the choice of bunch length. But bunch length reduction can only be sought at the expense of increasing transverse dimensions (increased emittance) or energy spread. The minimum achievable bunch length is limited by longitudinal space charge, the increase in the energy spread and non-linearities in the RF voltage. Bunch compression will primarily be performed in the recirculation loop to avoid Emittance growth in the low-energy beam transport and to minimize HOM excitation in the main linac. Conventional dipole chicanes and compression in the return arcs are approaches that have to be studied. Modest velocity bunching in the booster and compression in the merger may also be studied. These techniques can generate short bunches in the linac for high-frequency HOM experiments. A number of these techniques have the potential of adversely affecting other critical ERL parameters, for example, the phase of the recovered beam and the energy spread. Hence careful attention must be paid to developing a complete solution that provides a good compromise.

Energy Spread and Beam Loss: bunch compression and radiation production in high-energy ERLs are the main sources of energy spread. A large longitudinal and transverse acceptance is essential to keep beam losses below 10^{-5}. This ensures efficient energy recovery, a good vacuum, low cryogenic load and in general prevents damage to the machine. Such challenging beam-loss control must be studied, both theoretically as well as experimentally with the appropriate diagnostic tools to measure these small losses. When the recirculated bunch is decelerated, the relative energy spread increases by the ratio of the initial to the final energy. Energy spreads up to a significant fraction of the final beam energy can be reached in the dump line. Therefore the design of the extraction and beam dump needs to be carefully considered.

Energy Recovery: different concepts of recirculation loops have been considered for ERLs in operation and those being proposed [3]. Issues of interest besides the emittance growth, the energy acceptance and the bunch compression are the path length variability, critical to match the bunch arrival time during deceleration to the RF phase. A magnetic chicane introduced between the two return arcs is the straight forward approach but it must be compatible with the bunch compression. Careful consideration must be also given to designing and testing optics that can handle a beam with widely varying characteristics to provide the flexibility of ERLs.

Beam Break-Up: an ERL is a multi-pass multi-bunch accelerator, as each bunch passes through the linac-cavities at least twice. An off-axis passage of a bunch through the cavity leads to the excitation of dipole HOMs whose field may deflect a subsequent bunch. Following recirculation, the bunch re-enters the linac displaced, thereby feeding even more energy into the mode. This positive feedback can potentially drive instabilities, if the current is so high that more energy is transferred into the HOMs than is extracted by the HOM couplers. Similar effects exist for monopole and higher multipole modes. The actual beam-break-up (BBU) threshold is determined by the HOM spectra of the cavities and the optics of the ERL. If it is insufficiently high, active feedback or modified optics may be required to increase the limit. Other techniques, such as randomized HOM spectra for the different cavities may also help. BBU must be carefully studied so that it can properly be predicted for large-scale facilities.

Ion Generation: the production of ions in the beam pipe through collisions with the rest gas is governed by a number of factors. Beam instabilities, particle loss and optical errors can occur where these ions create a highly nonlinear potential in the vicinity of the beam. This is especially important in future ERLs with the highest currents, and methods to mitigate the problem must be developed. These include gaps between bunch trains as well as utilizing clearing electrodes. By varying the bunch-gaps and electrode voltage and measuring the betatron phase variation in the linac, ion trapping can be evaluated and

CW SRF Cavity System

The high average current in an ERL requires a CW machine operation. Together with the need for a high gradient in the rf cavities superconducting accelerating techology is a key aspect for ERLs. The basic superconducting linac technology has been developed and demonstrated with great success in facilities such as FLASH, which uses pulsed TESLA technology [4]. For several years, extensive studies at HZB-ME/BESSY with HoBiCaT have already served to adapt this to CW operation [5, 6]. Other institutes, such as Cornell University, FZ Dresden-Rossendorf and Daresbury Laboratory have also been modifying various aspects of TESLA technology for CW linacs. It will therefore also provide the baseline for B*ERL*inPro. For ERLs, though, further significant changes are required.

Electron Source: the ultimate performance of the ERL depends on the ability of the electron source to deliver a high brightness, high-average-current electron beam to the main accelerator complex. The highest bunch repetition rate should match the fundamental accelerator frequency of 1.3 GHz (see below), to minimize the bunch charge and hence the achievable emittance. A variable ERL source must provide an average current of order 100 mA, with approximately 50-100 pC bunch charge at about GHz repetition rates and a normalized Emittance better than 1 mm mrad. For maximum flexibility, the source must also be able to generate pulses of higher charge at lower repetition rates to meet specific experimental needs. SRF photoinjectors have the greatest potential and flexibility, as they are able to operate at 100% duty factor and can generate significantly higher fields than (CW-operated) normal conducting RF (NCRF) and DC systems. Most importantly, they offer the most potential for continued future improvements, so vital to the upgrade of ERL facilities. One of the primary goals of the B*ERL*inPro facility will therefore be to demonstrate that a high brightness, high-average-power electron beam can be generated and maintained by a photo-driven SRF gun. The main challenges for this system are:

- The cathode/cavity interface.
- Achievement of the highest accelerating field by employing appropriate treatment techniques.
- Cathode lifetime and techniques for rapid cathode exchange.
- The emittance compensation scheme.

Injection System: the injection linac is a short acceleration section that boosts the beam energy from the gun to approximately 5 - 10 MeV. This beam energy is not recovered during the later deceleration phase because the relative energy spread produced in the undulators and bends will amplify during deceleration, thus preventing energy recovery down to near-zero energy. Consequently, the booster module must provide the full beam power (500 - 1000 kW @ 100 mA), placing stringent boundary conditions on the SRF hardware and the beam dynamics. The voltage provided by each cavity is limited by the average RF power that can be coupled to the beam, rather than the achievable peak field. This must be contrasted with the current SRF-cavity development for projects such as XFEL and ILC, where the maximum attainable gradient is being pushed. Not only must suitable high-average-power RF sources be developed, but more critically, the RF input coupler system has to handle the large thermal loading associated with > 100 kW of RF power operation, approximately five times more than established systems can handle. The large beam loading also requires that the input coupler strongly couples to the cavity to transfer the RF power to the beam. This leads to beam disruption. Coupling schemes to minimize this are thus an important aspect of the booster module (and gun-cavity) design.

SRF Main Linac: the SRF main linac encompasses the part where the beam energy later is recovered. Here the effective beam loading is negligible, provided energy recovery is efficient, and these units are not affected by the coupling issues of the booster cavities. Still, a number of other aspects will need to be addressed.

Higher-Order Modes: common to the booster, the cavities must handle a large current (> 100 mA). This is compounded if multi-turn acceleration is implemented. For ps long bunches, as much as 100 W/m of higher order mode (HOM) power can be generated, with a frequency spectrum out into the 100-GHz range. Optimizing the cavity shape and number of cells is an important method to reduce the HOM power in the first place. But the remaining HOM power must be extracted with specialized HOM absorbers in the cryostat that guarantee efficient power extraction with minimum beam disruption. The beam disruption can only be studied when a high-current beam is accelerated which is used to excite the higher order modes. Under certain circumstances, modes can also be trapped in the multicell cavity structure, and are invisible to the absorbers and pickup probes. They will, however, communicate their presence to the beam which therefore serves not only to excite the modes but also is an important diagnostic tool.

Field Stability: for future experimental users of ERL facilities, the pulse-to-pulse timing stability and synchronization to a master clock will be an important requirement, especially for dynamic experiments at the sub-ps level. This ultimately translates into stringent stability requirements for the electron-beam and hence the source and the accelerating cavities. Phase deviations in the cavities can also affect the bunch profile whenever this is manipulated in the linac (e.g., bunch compression). Similarly, the efficiency of energy recovery will be determined by the phase stability of the beam. In particular, microphonics are expected to be a dominant noise source and their strength must be measured during module operation. Important results to stabilize CW cavities against microphonics have already been gained in the HoBiCaT developments at HZB [7]. They need to be implemented under realistic accelerator conditions to demonstrate their flexibility, robustness and long-term reliability.

Cryogenic Load: the main linac of an X-ray ERL represents by far the dominant cryogenic load and hence is a significant cost driver both in terms of capital investment and operating costs. For the feasibility of future ERL facilities, it must therefore be demonstrated that lowest-loss (high Q-factor) cavities can be produced and operated over the long term in an ERL system. Many factors contribute to the losses, from insufficient magnetic shielding, to preparation techniques and cavity material, to the actual cavity shape and operating temperature. All these must be optimized and their benefit demonstrated in a fully operational module. This focus is in contrast to the present cavity development for XFEL and ILC, where the emphasis is on maximizing the (pulsed) field rather than improving the quality factor. Templates are provided for recommended software and authors are advised to use them. Please consult the individual conference help pages if questions arise.

DESCRIPTION OF THE B*ERL*inPro FACILITY

As shown in Figure 1, B*ERL*inPro will be located in an extension of an existing assembly hall (Schwerlasthalle). The building also houses the HoBiCaT facility which already is used extensively for off-line cavity and subsystem testing in collaboration with DESY, FZD, CEA-Saclay and INFN Milano. Furthermore, an extension of HoBiCaT will provide room for a gun test stand to enable rapid gun development. Thus all B*ERL*inPro development facilities will be in close proximity to another. An important first stage of the B*ERL*inPro program will be the in-depth development of anoptimized layout. However, even now one can specify the general layout of the facility, as indicated in Figure 2, its main parameters being listed in Table 1. This represents the minimal arrangementrequired

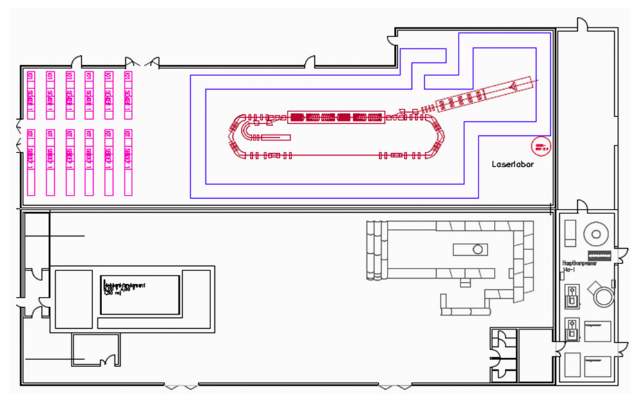

Figure 1: Layout of B*ERL*inPro in the extension to the existing Schwerlasthalle. The cryogenic facility and HoBiCaT, with room for a gun test stand, will be in close proximity to the prototype facility.

Table 1: Main Parameters of B*ERL*inPro

maximum beam energy	100 MeV
maximum beam current	100 mA
nominal bunch charge	77 pC
maximum repetition rate	1.3 GHz
normalized emittance	< 1 mm mrad
cryogenic load at 1.8 K	240 W

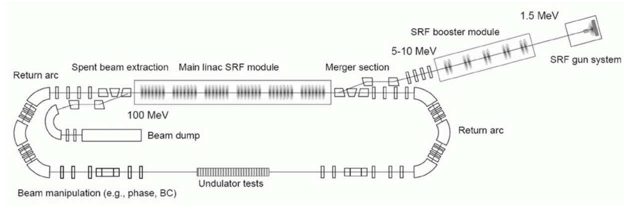

Figure 2: Schematic of the main components of B*ERL*inPro.

for the experimental investigations discussed above. An SRF photoinjector will serve as the beam source. A combination of RF focusing and solenoidal field provides the first stage of the emittance compensation scheme, which continues through a booster module. The beam must then be inserted into the main linac at a small angle, which is accomplished with a merger section consisting of several bending magnets. The main-linac acceleration to 100 MeV is provided by a 1.3-GHz superconducting module to be developed. Recirculation is done in a race-track configuration through optics with a high degree of flexibility to configure B*ERL*inPro for the various studies. Also, undulators such as the HZB APPLE III devices or the FZ Karlsruhe superconducting short-period system can be tested with a low emittance beam in the straight section. Finally the beam is extracted after deceleration into a highpower beam dump. Importantly, the B*ERL*inPro site is chosen in such a manner, that a second recirculation arc can be implemented in a future upgrade of the facility. This would increase the beam energy to nearly 200 MeV and permit important studies of multi-turn energy recovery, an aspect that has not yet been studied with superconducting ERLs and which may be of great importance for future facilities.

Electron Source

A CW operated SRF photoinjector will be the electron source for B*ERL*inPro. It will be developed in a staged approach [8]. The design parameter for the final gun will be a frequency of 1.3 GHz, an energy gain of up to 1.5 MV and peak field of 50 MV/m. The maximal average current will be in the regime of 100 mA.

Booster RF System

A booster appropriate for use in B*ERL*inPro is shown in Figure 3 and is currently being commissioned by Cornell University [9, 10]. The module contains five 2-cell, 1.3-GHz niobium cavities each equipped with two high-power RF couplers to both symmetrize the fields and increase the available RF power to 150 kW [11]. The RF system is capable of accelerating 100 mA to 5 MeV, or 33 mA to 15 MeV. Newly developed HOM beam-tube loads between the cavities are designed to absorb the large amount of high-frequency HOM power at 80 K, to minimize the heat load to the liquid helium. Importantly, each cavity will be powered independently. Not only does this permit the maximization of the performance, but it also enables independent phasing of the booster cavities. This scheme provides for a large degree of flexibility for beam manipulation, including velocity bunching, to perform the numerous studies outlined earlier and to optimize the emittance compensation process. Both the booster and photoinjector RF systems have the same requirements, these being limited by the capability of the 75-kW input couplers. Each cavity will be fed by its own 150-kW transmitter through two input couplers. 120-kW IOT or 150-kW klystron tubes, both developed by CPI, are currently being considered. The transmitter will be based on technology already developed and in operation at HoBiCaT and the MLS facility built by HZB. Prototyping of the low-level RF-control system is well under way at the HoBiCaT facility. RF control will be provided by adigital, FPGA-based system as described in Chapter 6 of the BESSY-FEL TDR [12].

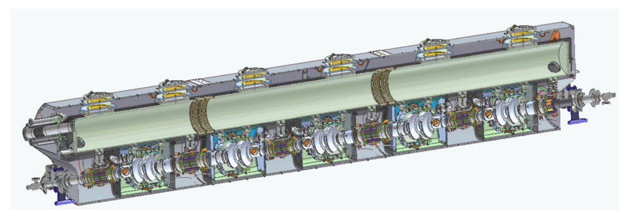

Figure 3: ERL booster module developed by Cornell University, a design suitable for B*ERL*inPro.

Main Linac Acceleration Module

Significant effort has been invested in developing TESLA technology since the early 1990's in anticipation of the construction of the next high-energy accelerator (now referred to as the ILC). Its maturity and reliability for light sources has been amply demonstrated by the TESLA Test Facility at DESY, now called FLASH. CW and high-current operation, as needed for ERLs, was not in the original portfolio of TESLA, but owing to its success, it is now being considered for numerous smaller CW machines, shifting the focus to highest Q, high-current operation. As outlined earlier, this will impact the design of both the cavities and module. First steps in this direction have already been performed by HZB in developing the BESSY-FEL modules [12, 13], although these were designed for low-current operation. Plans now call for a collaborative development of a high-current, low-beam-loading module between Cornell University and HZB, starting from the TESLA module design. Modifications to the cavity design and number of cells will serve to reduce the HOM excitation, minimize the risk of modes being trapped, to improve the HOM extraction and to reduce the cryogenic load. Special beam-tube HOM absorbers located between cavities and cooled to 80 K will reduce the load on the helium system. Apart from optimizing the cavity shape to reduce the cryogenic losses, other techniques may also flow into the module design. These include reduced trapped magnetic flux by employing better magnetic shields, such as double or triple shields, and special treatment techniques such as electropolishing and low-temperature bakeouts. Furthermore, cavity operation will be at 1.8 K or lower to reduce the BCS losses. For many of these, HoBiCaT represents an ideal facility for off-line tests on the complete cavity units, before the ideas are integrated into the module design. The cavities will operate at less than 20 MV/m for 100 MeV beam energy. As measurements in HoBiCaT have shown, Q-factors of order $2 \cdot 10^{10}$ are possible. Even for $Q = 1.3 \cdot 10^{10}$ and including static losses, the total cryogenic load of the module is expected to be less than 150 W. The RF system will be identical to the one planned for the BESSY FEL (see [12], Chapter 6). For flexibility and reliability it will consist of one 15 kW transmitter for each cavity with RF power supplied via coaxial transmission lines. A number of IOT tubes, favored because of their efficiency, are currently being tested in HoBiCaT. 10 kW RF power is sufficient for 20-MV/m operation, given peak microphonic detuning around 25 Hz and negligible beam loading.

Cryogenic System

The cavities of B*ERL*inPro are cooled with superfluid He at 1.8 K. As shown in Figure 4, the cryogenic system consists of two essentially independent parts: a liquefier to cool helium at room temperature to 4.2 K and a sub-cooling system to cool helium from 4.2 K to 1.8 K. The cold helium is provided by two medium-size cryogenic plants which are part of the BESSY II installation, providing liquefaction rates of 6 g/s and 23 g/s at 4.2 K. The 1.8-K sub-cooling unit, based on a combination of warm and cold compressors, must still be added for B*ERL*inPro. HZB has extensive experience operating a *Linde TCF50* cryoplant for BESSY II (4.2K) and HoBiCaT (1.8 K). The upgrade of the system with a *Linde L700* plant to increase the capacity for current activities is in operation. Both plants are connected at the 4.2 K temperature level by a cryogenic line, so that the full liquefaction power can be merged in a big 10.000 l dewar and is available for B*ERL*inPro. The capacity represents about 150% of that required for B*ERL*inPro.

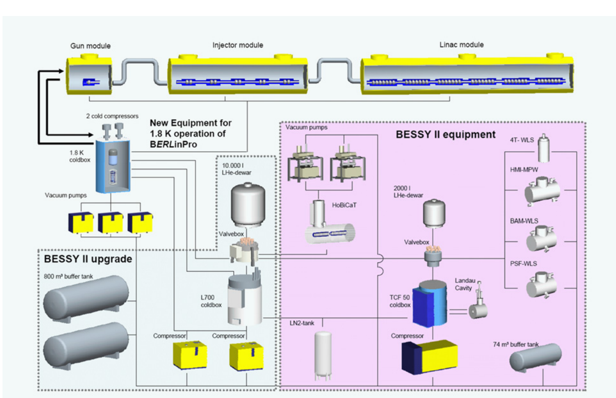

Figure 4: The cryogenic plant for B*ERL*inPro.

OUTLOCK

A first prototype of a SRF gun [8] is planned to be installed and tested at the HoBiCaT facility in 2010. The realization of the B*ERL*inPro facility is expected to be in 2011 until 2015.

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