THE SUPERCONDUCTING CW DRIVER LINAC FOR THE BESSY-FEL USER FACILITY*

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Abstract

A CW FEL User Facility for the VUV to soft X-ray spectral range using a cascaded HGHG-FEL scheme is planned at the BESSY site. Beam acceleration to 2.3 GeV is provided by a 144-cavity superconducting driver linac based on TESLA technology modified for CW operation. Initially, a high-rep-rate normal-conducting photoinjector will be used but a fully CW superconducting version is being investigated for a future upgrade. The required 2 kA peak current is achieved with two bunch compressors. An overview of the linac layout is provided here. Also discussed are the impact of CW operation, modifications to the TESLA technology that are necessary, as well as the expected linac performance.

INTRODUCTION

Numerous CW FELs are now being proposed to meet the demand of the synchrotron-light community for high-brilliance, fully coherent and short-pulse (fs) light in the VUV to x-ray range. These include the BESSY FEL in Berlin, whose Technical Design Report was published recently[1], and the 4GLS at Daresbury[2].

Such CW machines, which must use superconducting cavities, are very attractive because their intrinsic high average flux and brightness enable multi-beamline operation at a level not possible with pulsed linacs. Furthermore, CW operation provides additional flexibility to tailor the bunch structure to the users' needs. Due to the success of the TESLA Test Facility (TTF) at demonstrating the reliable operation of TESLA technology[3] for FEL applications, these new proposals are also based on this technology.

The BESSY-FEL facility, shown schematically in Fig. 1, comprises a CW linac driving three cascaded High-Gain-Harmonic-Generation (HGHG) FELs. These cover a continuous photon-energy range from 24 eV to 1000 eV.

For efficient lasing, the linac must provide a beam energy of 2.3 GeV at a peak current of 2 kA (2.5 nC per bunch) with a slice emittance of order 1.5 π mm mrad. Bunch compression is achieved in a two-stage system. An arc is included in the layout to reduce the physical length of the machine, leaving space for future upgrades and expansions. Fast kickers[4] at 1020 MeV and 2300 MeV then distribute the electron beam among the three FELs. A collimator section[5] prior to each FEL protects the undulators.

Although much of the pulsed TESLA technology will be transferred directly to the BESSY FEL several issues

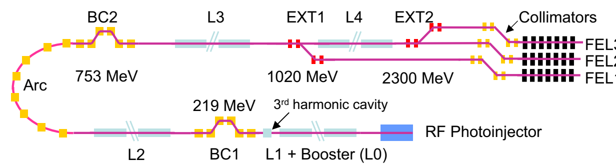

Figure 1: Layout of the driver linac for the BESSY FEL.

unique to CW operation have been investigated and necessitate some design and layout changes. These include cryogenic aspects, RF control and the RF distribution which are addressed later.

INJECTOR

Initially the injector will use a high-rep-rate normal-conducting (NC) RF photogun, but a future upgrade to a fully CW superconducting system is planned.[6] The NC gun is based on the operational PITZ design, which has achieved a *projected* emittance of 1.7 π mm mrad at a peak cavity field of 40 MV/m. Simulations of a layout optimized for 2.5-nC operation have demonstrated that, given a 38 ps flat-top temporal laser profile with short rise and fall times (4 ps), a slice emittance of less than 1.5 π mm mrad can be achieved at the exit of the booster section (L0) (2.1 π mm mrad projected emittance).[6]

Three bunches are accelerated in a 6 μs pulse at a repetition rate of 1 kHz. They are distributed among the three FELs using high-speed kickers[4], so that each FEL is also operated at 1 kHz. But the relatively large duty factor (ca. 2.5% when rise and fall times are included) produces a 75 kW heat load in the RF gun, nearly three times that of PITZ, so that the cooling had to be improved.

The NC, pulsed injector represents a conservative system that will be used to commission the BESSY FEL. However, to fully exploit the CW capability of the main linac, a CW injector will eventually be required. Such systems are currently being investigated[7, 8]. A split superconducting cavity/compensation solenoid layout is also being studied at BESSY. Preliminary simulations of such a layout suggest that the required slice emittance can be achieved at an accelerating field of 34.5 MV/m.

The L0 section, consisting of eight TESLA cavities, follows directly after the RF gun. The average field is 15.7 MV/m, chosen to minimize and preserve the emittance out of the gun. Acceleration is off crest, as in the L1 and L2 linac, to provide an energy chirp which later is used for bunch compression. A third harmonic cavity compensates for the curvature of the RF field as well as the T_{566} of the dispersive sections downstream.

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MAIN LINAC

Modules and cryogenics

The main linac consists of a further 17 TTF-style modules housing eight 9-cell cavities each (Fig. 2(a)). Details of the original TTF design and its philosophy are given in numerous references.[9, 10, 11] As in TTF, several modules are grouped together into cold sections.[12]

For a linac energy of 2.3 GeV, the average field is a conservative 15–16 MV/m. This was chosen for a number of reasons:

- Simpler cavity preparation. Cavities operating at 20 MV/m are now produced and assembled routinely.
- Improved reliability of the linac. Underperforming cavities can be compensated for by increasing the field of others, while remaining below 20 MV/m.
- High Q values can be achieved.
- Manageable cryogenic load per cavity.

Assuming a (measured) 2.0-K Q factor of 1.3×10^{10}[13] the average dynamic heat load is of order 20 W/cavity, for a total of 2.8 kW. However, the linac is designed for 1.8-K operation, and an improvement to $Q \approx 2 \times 10^{10}$ is expected, therefor reducing the cryogenic cost significantly.

Compared to TTF, the heat load per cavity still is 10 to 20 times greater. To exhaust this heat, the helium-tank design was modified slightly. In particular the diameter of the two-phase supply line spanning the modules and the chimney supplying helium II to each tank were enlarged to 100 mm and 90 mm (ID), respectively, as shown in Fig. 2(a).

For the helium distribution, the scheme in Fig. 2(b) was chosen. This creates two independent legs of nearly equal length. The main advantages lie in the ability to operate/commission the two sections independently and a reduced pressure drop in the gas return pipe (GRP) that returns the helium to the refrigeration plant.

Simulations of the cryogenic distribution system with a 4.5-kW heat load (roughly a 100% safety margin) have been performed to better understand the He flow and pressure drop given the large heat load. These simulations demonstrated that stable stratified two-phase flow is maintained in the entire linac (see Fig. 2(c)), provided always eight cavities are supplied with He-II by a JT valve, as in Fig. 2(a) (18 supply valves in total). This is in contrast to the layout for the XFEL, where only one JT valve for every 10 modules is required.

RF system

Beam loading will be, at most, 1.5 kW/cavity, so that each cavity is equipped with its own RF transmitter. This provides a large degree of operational flexibility and reliability and improves the RF control.

However, the cavity bandwidth is small (order 10–50 Hz) and microphonic detuning increases the *peak* power demand to about 15 kW while the average power is less than 5 kW.[1] For such operation, IOTs have a higher efficiency than klystrons. Two systems have been developed for 1.3 GHz so far (E2V & CPI VKL7811) and they will be evaluated in the HoBiCaT facility[15, 16] to test their suitability for the BESSY FEL.

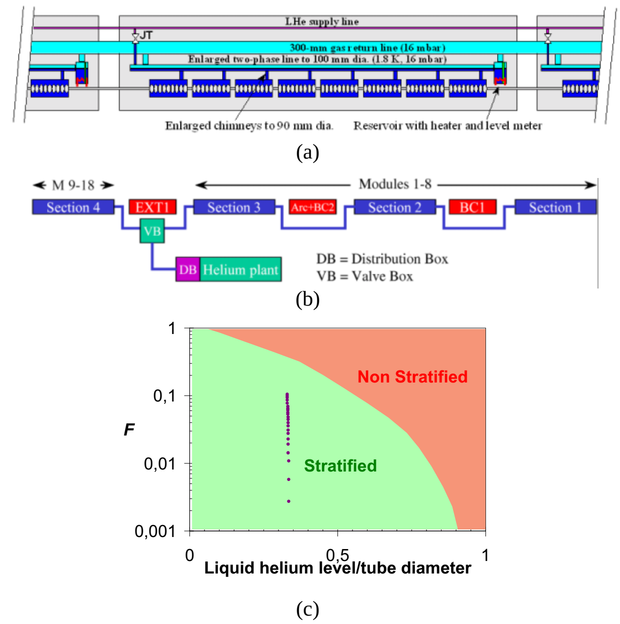


Figure 2: (a) Schematic of the CW module, (b) Helium distribution in the BESSY FEL. (c) Simulated flow pattern for 1.8 K He II in the two-phase supply line of the most critical module. The dimensionless parameter F, as defined in [14], determines whether flow is stratified or not.

TTF type-III couplers[17] in conjunction with waveguide tuning stubs provide the coupling to the cavities. This combination yields a coupling range of nearly two decades which not only offers the flexibility to adapt cavities to changing beam-loading conditions and performance, but also enables high-power processing of cavities.

To compensate the beam loading and microphonics of order 5 Hz rms, about 4–5 kW CW RF power is needed per cavity for 20 MV/m operation. The coupler has been tested to 4 kW CW at Rossendorf, this being limited by the heating of the inner-conductor bellows. However, this coupler was tested warm and a further increase under normal (cold) operating conditions is expected. Cold tests will be carried out in the HoBiCaT facility soon. Also, design changes required to significantly boost the power capability (50 kW) have already been identified, should the need arise.[18]

RF control will be implemented using a digital FPGA-based system. This is currently being developed for testing in HoBiCaT.[19] For efficient light generation, the HGHG scheme requires a bunch-to-bunch energy stability of 10^{-3} and a timing jitter of less than 50 fs at the linac exit.

Simulations were made to better understand the achievable performance of the linac. For these, the cavity voltage was evolved in time in the presence of beam loading, microphonics, Lorentz-force detuning, and other noise terms. The beam was tracked through all 144 cavities, as well as

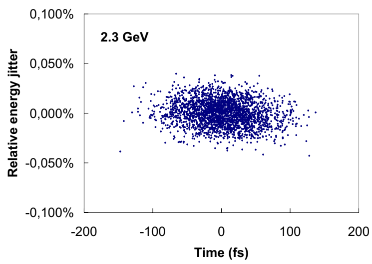


Figure 3: Simulated bunch-to-bunch energy distribution.

the bunch compressors and 3rd-harmonic cavities.

Although a number of the assumed initial conditions still need to be verified experimentally, these simulations have demonstrated that the requirements for energy and time jitter can indeed be met. Fig. 3 depicts one result of the jitter at 2.3 GeV. The dominant noise source are the microphonics, an rms value of 5 Hz being assumed, and the energy/phase jitter of the injector. Passive and active means of reducing the microphonics will be investigated in HoBiCaT. In particular, piezo compensation potentially can improve the cavity performance significantly and will likely be implemented in the BESSY FEL.

Bunch compression

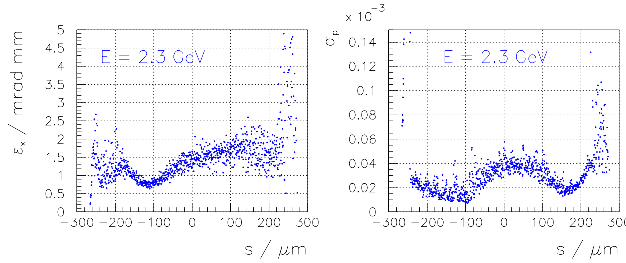
In principle, the bunch compression could be done in one step. Non-linearities arising from wakefields, coherent synchrotron radiation (CSR) and space-charge effects, however, limit this and a two-stage scheme was adopted for additional flexibility. This was optimized in view of the emittance, peak current and energy spread at the linac exit.

By accelerating off crest at -13.3° in the L0 and L1 section, and at -5° in the L2 section the longitudinal energy profile is chirped. This is then translated into a bunch shortening in the dispersive bunch compressors.

The first bunch compressor (BC1) was placed at the lowest possible energy (219 MeV) to minimize the summation of non-linearities imposed by the RF potential on the relatively long bunches. An energy limit is set by space charge effects. A six magnet chicane, rather than four, was chosen to reduce the magnet strengths, thereby avoiding emittance dilution due to CSR effects.

The arc must be placed before the second bunch compressor (BC2) to avoid strong CSR effects due to short bunches. BC2 then follows immediately so that adiabatic damping does not diminish the energy chirp unnecessarily. The arc/BC2 combination is placed at the highest possible energy to save space and to increase the beam's rigidity, thereby reducing its sensitivity to disturbances. This energy is limited by the CSR effects in BC2 to about 750 MeV.

Eight dipoles are used in BC2, again to reduce their strength and hence CSR effects. Two additional quadrupoles provide extra control of the beta functions. The arc, which "naturally" would have a positive momentum compaction, has been tuned to be isochronous to prevent bunch lengthening that otherwise would have to be compensated for in BC2 by an increased field strength.



(a) (b)

Figure 4: Slice analysis of the beam simulations at the collimator exit.[1] (a) Emittance, (b) relative momentum.

START-TO-END SIMULATIONS

Several programs were used to simulate the full BESSY FEL.[1] Calculations from the gun to the first bunch compressor (where space-charge-effects cease to be important) were performed with ASTRA using 100,000 particles. The 6-D phase-space output was then converted and passed on to ELEGANT for calculations up to the linac end. Finally, calculations of the HGHG scheme were performed in ELEGANT. The slice emittance of 1.5 π mm mrad, as shown in Fig. 4(a), is preserved throughout the linac. Also the slice momentum spread (Fig. 4(b)) is less than 5×10^{-5}. Both values are well suited for the HGHG cascade.

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