

Radiation Generation with an Existing Demonstrator of an Energy-Recovery Continuous-Wave Superconducting RF Accelerator

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Over the past decades, many accelerator laboratories have put much effort into the development of compact energy-recovery linac (ERL) demonstrators to verify various physical and technical aspects of the generation, acceleration, transport and energy recovery of high brightness and high average current electron beams in a superconducting radio-frequency (SRF) linear accelerator. Beyond these goals, the ERL demonstrator also offers unique opportunities to study novel schemes for THz and X-ray radiation generation. In this paper, we discuss feasible options for schemes generating THz and X-ray radiation at low-energy continuous-wave (CW) SRF ERL demonstrators such as the bERLinPro accelerator.

Keywords: THz source, Energy recovery linac demonstrator, bERLinPro
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I. INTRODUCTION

During the past two decades, the design and construction of energy recovery linear accelerators (ERLs), such as cERL in Japan [1], bERLinPro [2], S-DALINAC [3], and MESA [4] in Germany, ALICE in UK [5], PERLE in France [6], CBETA [7], ER@CEBAF [8] and CeC@RHIC in USA [9], and NovoFEL in Russia [10], have been carried out all over the world to demonstrate key technologies for a GeV-scale energy-recovery linac (ERL)-based radiation source. Almost all of these accelerators utilize continuous-wave (CW) superconducting cavities to accelerate ultra-bright electron beams in 6-dimensional phase space at high repetition rates. This combination is substantial for obtaining high average and peak brightnesses as in lightsources based on storage rings, where the only task of accelerating cavities is to replenish losses arising from the emission of synchrotron radiation. Recently, the fundamental technology developments of a superconducting radio-frequency (SRF) high-power electron gun, high quantum efficiency photocathode and high-gradient accelerating cavities have been coming together gradually and the operational techniques for energy recovery have been proven with a beam current of 5–9 mA [11, 12].

Here, we want to discuss science cases and applications

beyond accelerator science research for bERLinPro [13], which is an ERL project and currently under construction at the Helmholtz-Zentrum Berlin (HZB) Institute in Germany. Various options have been discussed at the 63rd ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs 2019 (ERL'19) and at a satellite meeting [14]. One option was to use the low-energy ERL demonstrator as a hadron beam cooler for collider experiments. For this purpose, ampere-class fresh bunches are required to achieve sufficient cooling efficiency [15, 16]. Another proposal was to investigate capabilities for the generation of the wavelengths from Terahertz (THz) to X-rays. ERL THz based research has gained significant attention over the past 20 years as sources and experiments have been developed in what was formerly a dark region of the electromagnetic spectrum [17]. Available space in the straight sections of the ERL provide an opportunity to install undulators or other special devices for future experiments to demonstrate the potential of ERLs for user applications. The high repetition-rate of the ERLs can easily achieve high average radiation power.

II. BERLINPRO

A sketch of the bERLinPro accelerator can be seen in Fig. 1. The bERLinPro injector, consisting of a photo-

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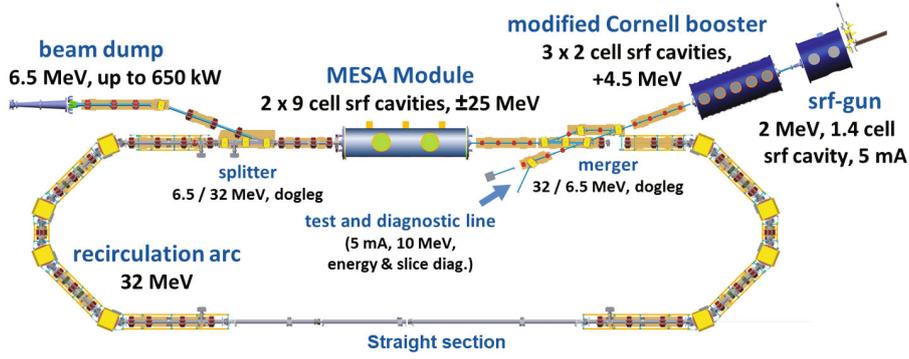


Fig. 1. bERLinPro - with a MESA module as the main linac.

Table 1. bERLinPro's main target parameters, initial project goals before descopeing parenthesized.

parameter	value
maximum beam energy / MeV	32 (50)
maximum average current ^a / mA	5 (100)
RF freq. & max. rep. rate / GHz	1.3
reference bunch charge / pC	77
normalized emittance / $\mu\text{m rad}$	1.0
bunch length (standard mode) / ps	2.0
bunch length (short pulse mode ^b) / fs	100
maximum losses	$< 10^{-5}$

^alimited by the gun maximum coupler power or to lower values by beam break up (BBU)

^bat reduced bunch charge

cathode SRF gun (1.4 cell), followed by a booster cryomodule containing three SRF cavities (2 cells), generates a high brilliance beam with an energy of up to 6.5 MeV. The beam from the injector is merged into the linac section by using a dogleg chicane. This section can handle beams with two different energies with a bunch spacing of 385 ps (2.6 GHz). Two beams, a low-energy fresh and a high-energy to-be-recovered beam, pass through the main linac to be accelerated and decelerated, respectively. Through a racetrack magnetic lattice, including a long straight section where optional experimental equipments could be installed, the accelerated beam will be recirculated to demonstrate effective energy recovery. The decelerated beam is sent into the dump line at low beam energy. The beam in the recirculator straight section has a transverse size of a few hundreds of micrometers ($\epsilon_{n,xy} \approx 1.0 \mu\text{m-rad}$, $\beta \sim 10 \text{ m}$, $\gamma = 63 \rightarrow \sigma_{xy} \sim 400 \mu\text{m}$) at 77 pC and a variable pulse length of 2 ps in the standard operation mode. In a dedicated short-pulse mode at reduced charge, the bunches can be compressed down to 100 fs or even less. The project's basic set of parameters is listed in Table 1.

Due to schedule, resources and budget reasons, a major descopeing of the project became necessary [18].

Thus, bERLinPro will be operated with an SRF gun that is expected to generate a maximum current of about 5 mA, which is determined by the installed RF power couplers. Also, the bERLinPro main linac had to be canceled and will not be part of the project anymore. However, acceleration and energy recovery is still planned in bERLinPro through a collaboration with the MESA project based at the Johannes Gutenberg-Universitt Mainz. With the so-called MESA option [19], the test operation of one of the two MESA-project [20] main linacs will give researchers a chance to characterize it with electron beams, to accelerate the beam in bERLinPro to an energy of about 32 MeV, and to demonstrate energy recovery. The operation period will start in the middle of 2021 and includes all steps from commissioning and recirculation to energy recovery.

III. THZ GENERATION IN BERLINPRO

Although efficient laser-based THz sources have now enabled novel experiments on specific sample systems, only accelerator-based THz sources provide wide tunability together with high intensities and high repetition rates beyond 100 kHz [21]. These advantages of accelerator-based sources will enable broad applications to the most interesting scientific problems in the field [17]. Particularly, the frequency range of 3 to 20 THz, where vibrational resonances and relaxations in condensed matter occur, is difficult to cover by using existing laser-based sources. In order to achieve high average and peak power at accelerator-based sources, we have to use coherent radiation, in which the radiation power is proportional to the square of the number of electrons. Coherent emission of radiation appears when the wavelength of the emitted radiation is significantly longer than the particle bunch length. The radiation spectrum can be represented as a sum of coherent and incoherent parts [22,23]:

$$P(\omega, \sigma_z) = p(\omega)(N_e + N_e(N_e - 1)g^2(\sigma_z, \omega)), \quad (1)$$

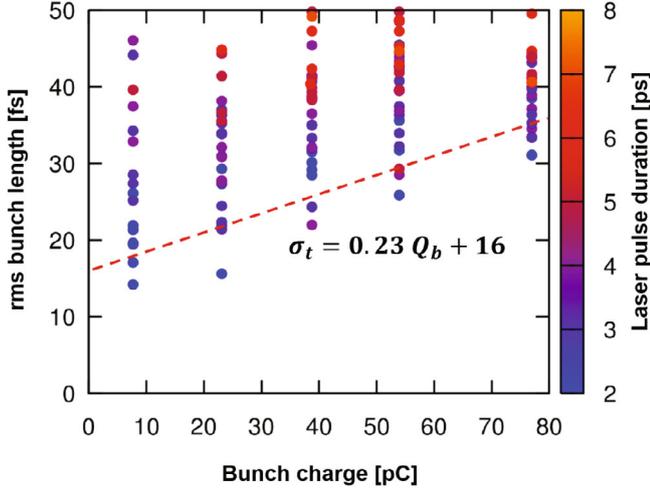


Fig. 2. Bunch length after compression as a function of bunch charge calculated for different parameter sets. The laser pulse length on the photocathode defines the color code. Details of the simulation are given in Ref. 28.

where $p(\omega)$ is the radiation power from one electron, $\omega = 2\pi f$, N_e is the number of electrons, and $g(\sigma_z, \omega)$ is the form factor. The form factor is given by the modulus squared of the Fourier transform of the longitudinal charge density of the bunch. For a Gaussian particle distribution, $g^2(\sigma_z, \omega) = e^{-\frac{1}{2}(\frac{\sigma_z \omega}{c})^2}$ is the form factor. The bunch form factor is equal to unity when the entire bunch acts as a single particle of enormous charge. For the generation of coherent radiation at frequencies of 1–10 THz, we need to produce a bunch shorter than the form factor limit ($\sigma_z \ll \sqrt{2}c/\omega$). In bERLinPro, bunch lengths between 20 ~ 100 fs can be achieved by using a two-stage compression scheme.

1. Bunch Compression

As we discussed above, one of the important questions for a THz source on the basis of the bERLinPro accelerator is, how short can the electron bunches be. The accelerator layout (see Fig. 1) and design of the magnetic optics for the accelerator are presented in Ref. 24. Bunch compression can be made in two compression stages by introducing a correlated linear energy chirp beforehand. The first possible stage includes the merger section in the injector. The necessary energy chirp is produced in the booster cavities. The limitations for the final bunch length after this stage are due to space-charge effects and the non-linearity of the RF field. The second stage uses a correlated energy spread produced by the main linac and the longitudinal dispersion of the recirculation arc. In this compression scheme, the final bunch length is limited by the coherent synchrotron radiation in the arc dipole magnets, as well as the 2nd and higher order aberrations of the magnetic optics. Particle tracking simulations are necessary to estimate how short the bunches

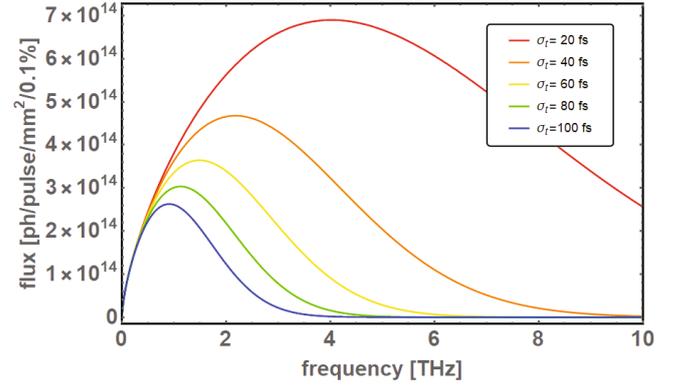


Fig. 3. Spectral distribution of the photon flux as a function of the bunch length with a dipole curvature of 0.78 m, a bending angle of 45 degrees, an angular acceptance of the beamline of 10 mrad, a bunch charge of 20 pC, a normalized emittance of 1 mm-mrad and an electron energy of 30 MeV.

can be and what is the optimal distribution of the compression between the two stages. The results depend on the bunch charge, laser pulse duration on the photocathode, and machine settings. ASTRA [25], CSRTrack [26], and Elegant [27] particle tracking codes were used for the simulations and optimizations of the machine settings for different bunch charges and laser pulse durations on the photocathode. A summary of the simulation results is shown in Fig. 2 [28].

The bunch length as a function of bunch charge is estimated from the fits to the average of a minimum of four cases of σ_t (fs) = $0.23 \times Q_b$ (pC) + 16, with a limit of 16 fs for zero bunch charge. Due to the strong space-charge forces at the shortest bunch lengths, a noticeable dilution, mainly of the horizontal emittance, cannot be avoided. However, the transverse emittance is still sufficiently small and well suited for the supposed THz-generation schemes.

2. Single-Cycle THz Generation by using Coherent Synchrotron Radiation

A bunch length of 20 fs, which corresponds to a form factor limit of 11.25 THz, can be achieved with a bunch charge of 17 pC, as extrapolated from the simulation results shown in Fig. 2. The dipole magnet installed in the recirculation arc is then a possible source of coherent synchrotron radiation (CSR) for intensive, wideband single-cycle THz radiation. This single-cycle short pulse allows studying fast dynamics, such as magnetic property switching in matter by electron paramagnetic resonance (EPR). The radiation power from one electron for synchrotron radiation (SR) is given by [29]

$$p(\omega) = \frac{\sqrt{3}e^2}{4\pi\epsilon_0 c} \gamma \frac{\omega}{\omega_c} \int_{\omega/\omega_c}^{\infty} dx K_{5/3}(x), \quad (2)$$

where e is the charge of an electron, ϵ_0 is the vacuum per-

mittivity, c is the speed of light, γ is the Lorentz factor, $K_n(x)$ is a modified Bessel function of the second kind, and $\omega_c = 3c\gamma^3/(2\rho)$ is the critical frequency, with ρ being the curvature of the electron trajectory. From Eq. 2, the critical frequency of the SR from the arc dipole magnet is about 18 THz for a dipole curvature of 0.78 m and an electron energy of 30 MeV. Thus, the wavelength of the radiation is mainly limited by the form factor. Due to the low electron energy, the SR has a relatively large divergence, $\Delta\phi = 1/\gamma = 17$ mrad. In order to confirm the achievable photon flux of the CSR from the dipole magnet, to calculate the spectral distribution as a function of the bunch length, we used the SPECTRA code [30] with an actual angular acceptance of a bERLinPro THz beamline and a bunch charge of 20 pC and the results are shown in Fig. 3. With a bunch charge of 20 pC and a length of 20 fs, the bERLinPro main dipole magnet in the recirculator can produce a photon flux of 6.7×10^{14} photons/pulse/mm²/0.1% B.W. up to a frequency of 11 THz with a bandwidth of 8.7 THz at full width at half maximum (FWHM).

3. High Pulse Power THz Generation by using an Insertion Device

A strong demand exists for high peak power THz radiation for studying the nonlinear (NL) behaviors and the irreversible processes (phase transitions) in matter. The requirement for this is mainly a high electric field on a sample of 0.2 GV/m with a wide bandwidth of up to 30 THz [17]. If a focus size diameter equal to the wavelength is assumed, the relation between the pulse energy J_{pulse} and rms electric field E_{rms} is given by

$$J_{pulse} = \frac{\pi\sigma_{pulse}c^3}{f^2}\epsilon_0|E_{rms}|, \quad (3)$$

where σ_{pulse} is the pulse duration and f is the carrier frequency. With a pulse duration of 1 ps (~ 10 cycles), a electric field of 0.2 GV/m then corresponds to a pulse energies of 3 mJ at 0.1 THz and 30 μ J at 1 THz. This pulse power can be obtained by installing an insertion device at the straight section of the recirculation arc, placed opposite to the linac section. If high-power SR pulses are to be generated in the THz region, an insertion device with a relatively long undulator period length of more than 18 cm is required. An in-house developed electromagnetic undulator (U180) [31], which is used for a metrology science application, can be applied to the bERLinPro accelerator. The undulator has an undulator period of 18 cm, a number of periods of 12, and a maximum K-value of 7.7. The pulse power is calculated using bERLinPro beam parameters. Figure 4 shows that a bunch charge of 160 pC can achieve a pulse power of 30 μ J at 1 THz and 3 μ J at 3 THz with the bunch length of 60 fs. From the measurement result of the quantum efficiency of 5% (laser power of 25 W) of the bERLinPro photocathode [32], the maximum bunch charge in

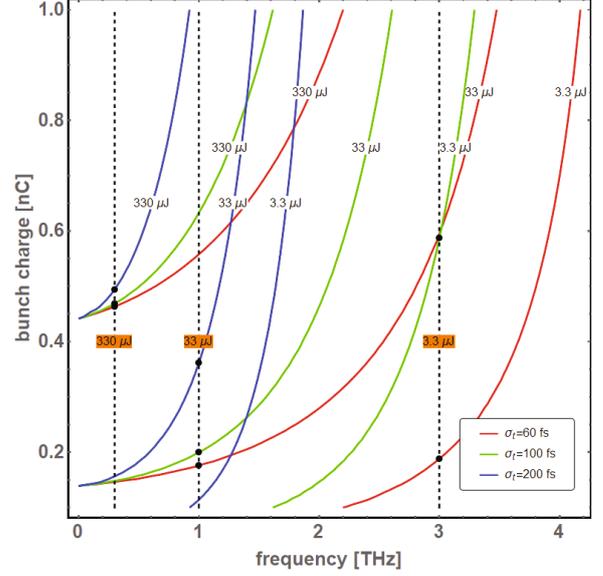


Fig. 4. Calculated SR pulse power with the specification of the U180 undulator as functions of frequency and bunch charge for bunch lengths of 60, 100, and 200 fs. The orange boxes show the pulse power required for an electric field of 0.2 GV/m at different frequencies. The dots represents the bunch charge required for an electric field of 0.2 GV/m.

the bERLinPro is about 350 pC. Because the average current of the SRF electron gun is limited to 5 mA, a bunch charge of 160 pC with a relatively low repetition rate can be generated at bERLinPro.

4. Compact THz Source by using Diffraction Radiation

Recently, a novel scheme for THz generation has been proposed and proven by Honda [33]. The method uses diffraction radiation (DR) as source and an optical cavity for amplifying the radiation power significantly through a stimulation process. When a relativistic electron bunch passes a hole in the center of a metallic disk, radiation is generated by the diffraction of the electric field of the electron bunch at the surface of the metallic disk. In accordance with Ref. 34, the DR spectral-angular distribution generated by a single electron crossing a symmetric metallic-disk with a hole radius of a can be represented by [35]

$$p(\omega, \theta_m) = \frac{2\alpha}{\pi^2} \int_0^{\theta_m} d\theta \frac{\theta^3}{(\theta^2 + \gamma^{-2})^2} \times \left[\frac{\omega b}{\gamma c} K_1 \left(\frac{\omega b}{\gamma c} \right) J_0 \left(\frac{\omega b}{c} \theta \right) - \frac{\omega h}{\gamma c} K_1 \left(\frac{\omega h}{\gamma c} \right) J_0 \left(\frac{\omega h}{c} \theta \right) \right]^2, \quad (4)$$

where α is the fine structure constant, θ_m is the polar observation angle, b is the outer radius of the disk, h

scenario described above. This would result in 2×10^4 photons per shot for a pulse length of 60 fs. Though the flux, if averaged over a MHz repetition rate, can be very high, the relatively large geometric emittance and the low beam energy lead to a large opening angle. Collimation would be required to allow efficient photon beam transport to the interaction region of the pump/probe experiment. Setting up the Compton interaction in a zig-zag geometry would lead to an increased photon flux and would even allow the Compton source to be operated in the two-color operation mode [39].

2. Electron Pulses for Ultra-fast Scattering

Another possibility to generate pulses to probe the atomic structure of matter is by electron scattering. Here, ultra-short relativistic electron beams at low bunch charge with $10^4 - 10^6$ electrons are focused on the experimental sample, and diffraction patterns are recorded or spectroscopy of the transmitted electron pulses is performed. The electrons are scattered by the Coulomb interaction with the binding electrons and with the protons inside the nucleus, so more information about the entire structure can be gained. For electron scattering experiments, the transverse coherence length of the electron pulses should be comparable to the domain size under investigation. The pulse length should also be shorter than 100 fs to allow dynamic studies of atomic motion.

We investigated an option to generate ultra-short electron pulses for scattering experiments in the beam diagnostic section behind the SRF gun and the SRF booster cavities. A highly coherent pulse is to be generated, a beam with a small spot size and low emittance needs to be launched in the SRF gun. This can be done by focusing the photocathode drive laser to extremely small spot sizes followed by rapid acceleration to keep emittance growth due to space charge effects under control. The ultra-short pulse length is generated by employing the SRF gun cavity and one SRF cavity in the SRF booster module for longitudinal phase space manipulation. With the so-called stretcher mode [40], the electron pulse at low charge is first stretched by acceleration at an off-crest phase in the SRF gun cavity and then longitudinally focused to a sub-fs pulse length at the interaction region with the SRF booster cavity [41]. In principle, researches should be able to interleave an ultra-low charge pulse with the electron pulses generated for the THz radiation process. The separation could be done with a fast RF kicker at the entrance of the merger beamline, where the high-charge pulses are fed on the axis of the main linac.

V. CONCLUSION

Various feasible schemes for generating high-power single- or multi-cycle THz radiation were studied with

the beam parameters for bERLinPro. The main dipole magnets in the recirculator can produce high-power single-cycle THz radiation, which is usable for THz ERP applications. The installation of an additional U180 undulator at the recirculator straight section and a compact diffraction radiation source can produce high-pulse-power multi-cycle THz radiation suitable for the study of nonlinear behavior or irreversible processes. Especially, the short bunch mode for bunch lengths down to 20 fs offers a unique opportunity for generating strong coherent radiation over a wide spectral range from 3 to 10 THz, which is the most difficult to cover by existing sources. In addition, the bunch charge of 10 pC to 200 pC is capable of being used to study the material properties in the linear and nonlinear region. Furthermore, the X-ray pulses generated by using inverse Compton scattering of laser photons and ultrafast electron diffraction can be used to perform a fast dynamics study with a pump and probe method.

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