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Compact high-power terahertz radiation source

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In this paper a new type of THz radiation source, based on recirculating an electron beam through a high gradient superconducting radio frequency cavity, and using this beam to drive a standard electromagnetic undulator on the return leg, is discussed. Because the beam is recirculated and not stored, short bunches may be produced that radiate coherently in the undulator, yielding exceptionally high average THz power for relatively low average beam power. Deceleration from the coherent emission, and the detuning it causes, limits the charge-per-bunch possible in such a device.

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In the past two years, there have been a number of papers published addressing the subject of producing THz radiation through the coherent synchrotron radiation (CSR) emission process [1–3]. These studies assume a storage ring source; the CSR is produced by coherent synchrotron emission from density variations at wavelengths short compared to the overall bunch length in the storage ring. Initial work focused on measuring, quantifying, and theoretically explaining [3,4] the early observations of transient bursting in this emission [5]. A recent work claims a steady THz source in a storage ring has been observed [6]. The primary purpose of this paper is to point out that recirculated linac-based sources of coherent THz radiation offer the promise of higher power compared to ring-based sources, primarily because the electron pulse lengths possible from recirculated linacs may be made shorter than the emission wavelength, whereas the emission in storage rings is limited by the density modulation possible. To illustrate the advantages of the recirculated linac approach, some ideas regarding compact THz sources are presented by a high level design of such a source.

Coherent synchrotron radiation [7], and more recently coherent transition radiation [8] and coherent undulator radiation (CUR) [9], have been used for a number of years for electron beam diagnostic purposes [10,11]. In a typical application one has a short bunch emerging from a linear accelerator, and the electromagnetic radiation emitted from the bunch by a bending magnet, a transition radiation foil, or an undulator, is measured and frequency analyzed. In the small source approximation the energy per unit frequency per unit solid angle emitted by a single passage of an electron bunch with N_e electrons through a radiator is

$$\frac{d^2E}{d\omega d\Omega}(\omega) = N_e \frac{d^2E}{d\omega d\Omega}\bigg|_{1e}(1 + N_e|S(\omega)|^2),$$

where $\frac{d^2E}{d\omega d\Omega}|_{1e}$ is the energy per unit angular frequency per unit solid angle emitted by a single electron, and $S(\omega)$ is the Fourier transform of the unit normalized bunch longitudinal distribution $I(z)$,

$$S(\omega) = \int I(z)e^{-i\omega z/c}dz, \qquad \int I(z)dz = 1.$$

Coherent emission occurs at those wavelengths at which the form factor, $|S(\omega)|^2$, is of the order of 1; at these wavelengths, typically longer than the bunch length, the energy goes as N_e^2, as does the power emitted by a continuous repetitive stream of such bunches. In the beam diagnostic applications, one usually concentrates on wavelengths comparable to the bunch length or larger, because it is at these wavelengths that the transition between coherent and incoherent emission occurs. In the fully coherent limit, notice that the total power emitted goes as the charge-per-bunch squared, and to get maximum emission it is advantageous to obtain as short a bunch as possible.

Recirculated linacs, the largest example of which is Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) [12], have a number of desirable features that may make them interesting light sources [13,14]. For example, such accelerators may have superior emittance than is possible in storage rings, and they may produce and accelerate to high energy short electron pulses [15], which may be used to produce short electromagnetic radiation pulses, much shorter than is typical in storage rings. It is sufficient to note that electron pulse lengths of under 100 fs (30 μm) rms have been observed at CEBAF with low bunch charge under 1 pC [16], and 360 fs (110 μm) rms has been observed on the Jefferson Lab infrared demonstration free electron laser (IR DEMO FEL) [17] at 60 pC bunch charge. These short longitudinal dimensions have been observed by a variety of techniques, including analysis of the spectrum of coherent synchrotron radiation and coherent transition radiation, as discussed above.

It is difficult to find high average power sources of coherent electromagnetic radiation for wavelengths between 0.1–1 mm (3–0.3 THz). This wavelength regime, sometimes referred to as the THz gap, is beyond the reach of typical microwave production techniques, and also in a

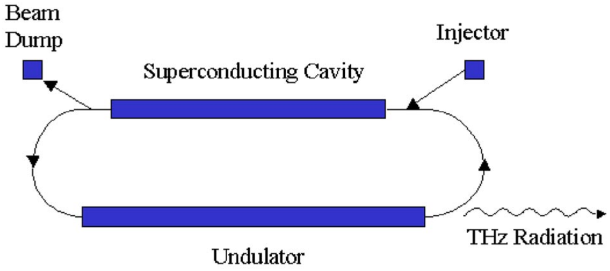

FIG. 1. (Color) Compact high average power THz source. The undulator is 1.25 m long in the case considered.

wavelength regime that is long enough that the strong transitions needed to construct a conventional laser are rare and difficult to use. Because the bunch length may be made smaller in a recirculated linac than the desired minimum wavelength, and because THz brilliance will be maximized by utilizing undulator emission, a device roughly as in Fig. 1 makes an interesting THz source. Some beam parameters are listed in Table I. A 300 keV beam of electrons of 100 μA average current originates from a photocathode gun. The beam is bunched with a single buncher cavity in the injector, and merged on the accelerator axis. In order to continue the bunching, the electron beam is accelerated slightly off crest. The first turnaround "arc" is chosen to have the correct M_{56} to yield maximum bunching at the undulator. After emitting coherent undulator radiation, the beam is directed back through the superconducting rf cavity on a decelerating phase. The beam is dumped at low energy and low beam power.

None of the parameters in Table I stretch the state-of-the-art terribly. For example, a single CEBAF 1497 MHz 7-cell superconducting cavity of length 70 cm will yield about 12.6 MV when operated at 18 MV/m. Such a gradient performance is below the requirements for the planned upgrade for CEBAF, and covers the full operating energy range from 0.3–3 THz as shown in Table II . The CEBAF accelerator routinely accelerates average currents of the order of 100 μA, and the Jefferson Lab IR FEL 5 mA. The most interesting parameter choice is the charge per beam bunch. Assuming an untapered undulator, because one would like the same undulator to cover a wide range of operating conditions, the charge per bunch is limited by the fact that beam deceleration from the coherent emission should not cause substantial detuning of the emission. If the beam is fully bunched longitudinally, the total energy of the coherent undulator emission, E_{CUR}, is approximately

$$E_{\mathrm{CUR}} = N_e^2 \frac{2\pi}{6} \alpha N K^2 h \frac{c}{\lambda} = \frac{4\pi^2}{6} \frac{N_e^2 e^2}{\lambda} N K^2, \qquad (1)$$

where N_e is the number of electrons in the bunch, α is the fine-structure constant, N is the number of undulator periods, K is the field strength parameter, λ is the emission wavelength, h is Planck's constant, and c is the velocity of light. The emission wavelength is related to the undulator period λ_0 by the usual free electron laser resonance condition

$$\lambda = \frac{\lambda_0}{2\gamma^2}(1 + K^2/2).$$

The electron bunch energy is $E_{\mathrm{beam}} = N_e \gamma m c^2$, and by requiring, conservatively, that $E_{\mathrm{CUR}}/E_{\mathrm{beam}} < 1/4N$, a bunch charge limit of

$$N_e < \frac{\gamma\lambda}{r_e} \frac{3}{8\pi^2 N^2 K^2}$$

is obtained where r_e is the classical electron radius. For 1 THz emission from a 5.7 MeV beam driving a 25 period undulator, the maximum bunch charge is about 12 pC, and for a 3 period undulator the maximum bunch charge is almost a nanoCoulomb. This limit is not a hard limit because tapering the undulator may yield a higher possible bunch charge in a "single-frequency" THz source design. However, the estimate is instructive in that it provides some indication of the maximum output from a general-purpose THz source, which is obtained by filling every possible accelerating phase in the accelerator with this maximum charge. In this case an estimate of the "maximum" power possible in this type of device is obtained,

$$P_{\mathrm{CUR}} < f_{\mathrm{rf}} \frac{3\alpha(1 + K^2/2)}{128\pi^3 N^3 K^2} h \frac{\lambda_0 c}{r_e^2},$$

where f_{rf} is the rf frequency of the accelerator. From a total power viewpoint it is advantageous to increase the bunch repetition rate, increase the undulator period, and decrease the number of periods and the field strength because this increases the charge per bunch possible.

Assuming the same beam properties and the same average current, the total THz power from storage rings is not as large. First, for energies typical in present day storage rings, undulators tuned to the THz band would have to have unrealistically long period length, and one is forced to consider sources based on coherent synchrotron radiation from the bending magnets in the ring. Next, by assuming that the beam has a density modulation at

TABLE I. THz source accelerator parameters.

Quantity	Value	Unit
Beam energy	3.1–9.9	MeV
Average beam current	100	μA
Charge per beam bunch	12	pC
Bunch repetition rate	8.3	MHz
Normalized rms beam emittance	5	mm mrad
Longitudinal rms emittance	10	keV degrees
rms bunch length at wiggler	300 (90)	fsec (μm)

TABLE II. THz source undulator and calculated optical parameters.

Quantity	Value	Unit
Undulator		
Period length	5	cm
Period number	3, 25	
Field strength, $K = eB\lambda_0/2\pi mc^2$	1	
Wavelength at 5.7 MeV	0.3	mm
Fundamental optical power	0.7, 5.9	W
Fundamental flux	0.9×10^{18}, 7.3×10^{18}	photon/s in 0.1% bandwidth
Fundamental brilliance	1.6×10^{13}, 2.8×10^{14}	photon/(s mm^2 mrad^2) in 0.1% bandwidth
Optical pulse length ($N\lambda$)	0.9, 7.5	mm

wavelength λ inside a Gaussian distribution with longitudinal extent σ,

$$I(z) = \frac{1-m}{\sqrt{2\pi}\sigma}\exp(-z^2/2\sigma^2) + \frac{m}{\sqrt{2\pi}\sigma}\frac{1}{1-\exp(-2\pi^2\sigma^2/\lambda^2)} \times \exp(-z^2/2\sigma^2)[1+\cos(2\pi z/\lambda)], \quad 0<m<1,$$

where m is the fractional longitudinal modulation, the total power radiated into each harmonic by coherent synchrotron radiation in free space is [18]

$$P_n \approx 0.52\frac{N_e^2 e^2 c}{\rho^2} n^{1/3} |S(n\omega_0)|^2,$$

where n is the harmonic number, ρ is the bend radius, and $\omega_0 = c/\rho$ is the fundamental angular frequency of the revolution. Summing the form factor around $n_0 = 2\pi\rho/\lambda$, and using the fact that the weak $n^{1/3}$ dependence of the spectrum does not change much during the sum, the total energy-per-turn radiated at wavelengths close to the modulation wavelength is

$$E_{\mathrm{CSR}} \approx 3.25\frac{N_e^2 e^2}{\rho} n_0^{1/3} \frac{\sqrt{\pi}\rho}{\sigma}\frac{m^2}{4} \ll E_{\mathrm{CUR}}.$$

Because this energy is radiated over the whole ring circumference, and because at longer wavelengths the emission is suppressed due to shielding effects, it is clear that such a source is not as powerful as the undulator-based source.

In Table I, the repetition rate has been chosen to provide a convenient and demonstrated average current to work with, 100 μA, consistent with 12 pC derived above. It should be borne in mind that an additional factor of 200 in average power is possible if a 20 mA injector is developed to fill every accelerating phase with 12 pC of bunch charge. Strictly speaking, beam recirculation and beam energy recovery are essential source design elements only in a device at high average current.

The beam quality figures in Table I are estimates based on measurements performed on the IR DEMO FEL at Jefferson Lab [17]. As can be demonstrated by a simple calculation, 10 keV degrees longitudinal emittance is consistent with $\sigma_E/E \leq 1/4N = 1\%$ and a bunch length of 90 μm. To manipulate the longitudinal phase space in the way needed requires a buncher with a cw accelerating voltage of about 200 kV, a merging region M_{56} of -13 cm (the same in Ref. [17], but at much lower energy), and accelerating off crest by 3.3° through the turnaround arc which has a bend radius of 20 cm and M_{56} of 63 cm. The dispersion at the undulator is 40 cm, a value that causes inconsequential growth of the spot size at the undulator.

Consistent with Table I, some undulator parameters and photon beam characteristics are given in Table II for two cases of interest: first a few transverse oscillation period undulator which will yield a relatively wideband source, and a 25 period undulator which yields a relatively narrow band source. Undulators with such parameters are by now entirely standard and well within the state-of-the-art. The average fundamental optical power is estimated using Eq. (1). The fundamental flux into a bandwidth $\Delta\omega/\omega$ is estimated as

$$F = fN_e^2\frac{\pi}{2}\alpha N\frac{\Delta\omega}{\omega}[JJ],$$

where $[JJ]$ is a standard Bessel function factor for which $K = 1$ is around 0.55 for fundamental emission.

A general estimate for the brilliance is [19]

$$B = \frac{F}{(2\pi)^2\sqrt{\sigma_r^2 + \sigma_x^2}\sqrt{\sigma_{r'}^2 + \sigma_{x'}^2}\sqrt{\sigma_r^2 + \sigma_y^2}\sqrt{\sigma_{r'}^2 + \sigma_{y'}^2}},$$

where $\sigma_r = \sqrt{\lambda N\lambda_0}/4\pi$, $\sigma_{r'} = \sqrt{\lambda/N\lambda_0}$, and the rest of the σ's are the transverse rms beam sizes and beam angular spreads at the undulator. Assuming a symmetrical β function of 1 m at the middle of the undulator, and the emittance in Table I, the rms beam sizes at the undulator are 0.62 mm and the angular spreads are 620 μrad. Now $\sigma_r = 1.5$ mm and $\sigma_{r'} = 15$ mrad when $N = 25$, and the brilliance is largely determined by the photon diffraction effects.

Even though the beam average current is only 100 μA, the average THz beam power is orders of magnitude beyond that available from other nonaccelerator sources, is comparable to the demonstrated recirculated linac driven THz source at Jefferson Lab which is physically much bigger, much more expensive, and requires a much higher average beam current and bunch charge [20], and is greater than the powers being talked about from storage rings [6].

In this device wavelength tuning may be accomplished in three different ways, two of which are well known from free electron lasers. Because the emission wavelength depends on the energy, covering the range 0.3–3 THz is accomplished by changing the electron beam energy between 3.1 and 9.9 MeV. Such changes are relatively easy to accomplish by (i) scaling the magnetic fields in the recirculation system by the energy ratio, (ii) adjusting the rf cavity operating amplitude down by the correct amount, and (iii) adjusting the rf cavity phase slightly to achieve maximum bunch compression at the undulator. One may also change the wavelength by changing the magnetic field strength in the undulator. This method is probably preferred for small frequency changes, but becomes cumbersome if a large change of frequency is to be accomplished. Because one is operating at low energy in this device, it is also possible to change the photon emission wavelength observed by observing at an angle to the undulator axis due to Doppler shift of the emitted frequency. There will be some reduction of flux and brilliance by observing off the forward direction, but this scheme may be preferred in cases where the overhead of resetting the accelerator conditions needs to be avoided.

There has been much recent activity within the storage ring community about utilizing storage rings as THz radiation sources. Better high average power THz sources, especially ones that might be of cost and size accessible to a university department, could allow much more rapid exploration of still uncovered science in the THz band. Linacs and recirculated linacs will always have a large advantage compared to storage rings regarding the ultimate compression of bunches possible, because storage rings will always be limited by quantum excitation of synchrotron oscillations [21]. Small superconducting storage rings, indeed not optimized for the production of THz, have been built and several hundred MeV beams can be stored in devices that fit in a large room. On the other hand, the device described in this paper, particularly in its low average current versions, has the potential to be a table top device.

In this paper a specific rendering of a compact THz source has been presented and, more importantly, a physical limit of the use of small recirculated linacs for producing THz has been explored. A main limit to bunch charge in such a source is the energy detuning due to the coherent emission of energy in the source itself. As this detuning goes down with the number of undulator periods and with the field strength, one tends towards undulators with smaller numbers of periods and smaller field strengths, consistent with one's ability to compress the bunches to short distances. This conclusion is in marked contrast to undulators designed for x-ray production in storage rings. Here one enhances x-ray flux and brilliance by building many periods with as short a period length as possible.

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