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Compact High Power THz Source

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Many recent papers address the problem of producing THz electromagnetic radiation by specially designed accelerators. In this paper the potential performance of a new type of THz radiation source is explored. The device is based on recirculating a beam through a high average gradient superconducting radio frequency cavity, and using this beam to drive a standard electromagnetic undulator on the return leg. Because the beam is not stored in a ring but recirculated, short bunches may be produced that radiate coherently in the undulator, yielding exceptionally high average THz power for relatively low average beam power. Due to the deceleration from the coherent emission, and the detuning it causes, one is limited in the charge-per-bunch possible, and such a limitation is estimated and discussed in this report. Utilizing a recirculating linac arrangement has many advantages. Because the whole beam acceleration system consists of a single (or a few) superconducting cavity(ies) about a meter long, the potential exists to have a remarkably compact device that is relatively inexpensive.

In the past year, there have been a number of papers published in this journal addressed directly or indirectly to the subject of producing THz radiation through the coherent synchrotron radiation (CSR) emission process [1-3]. These studies have been performed on storage rings, and the CSR is produced by microbunching in the relatively long bunches present in the storage rings, that is by coherent synchrotron emission from density modulations at wavelengths short compared to the overall bunch length. 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 ring-based sources of coherent THz radiation will probably not be competitive with recirculating linac based sources, primarily because the electron pulse lengths possible from recirculating linacs may be made shorter than the emission wavelength, whereas the emission in storage rings is limited by the microbunching possible. To illustrate the advantages of the recirculating 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 [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

$$\frac{d^2E}{d\omega\, d\Omega}(\omega) = N_e \left.\frac{d^2E}{d\omega\, d\Omega}\right|_{1e} \left[1 + N_e |S(\omega)|^2\right],$$

where $\left.\frac{d^2E}{d\omega\, d\Omega}\right|_{1e}$ 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 order one; 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 typically 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.

It is becoming widely known that 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 (and hence higher photon brilliance) 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. For the purposes of this letter, it is sufficient to note that electron pulse lengths of under 100 fsec (30 micron) *rms* have been observed at CEBAF with low bunch charge under 1 pC [16], and 360 fsec (110 micron) has been observed on the Jefferson Lab IR DEMO FEL [17] at 60 pC bunch charge. These short longitudinal dimensions have been observed by a variety of techniques, including analysis 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 wavelength regime that is long enough that the strong transitions needed to construct a conventional laser are rare and difficult to use. Up until fairly recently, the best sources were thermal glowbar sources for wide band production, or conventional laser-based sources that rely on non-linear mixing for narrow band, low power sources. Conventional storage rings have been used for a number of years to produce shorter wavelengths in the infrared by incoherent emission, but because of the relatively long bunch length present in most storage rings (> 3 mm), it has been very difficult to observe any coherent emission. It is only recently that a ring has produced microbunching at short enough wavelengths and so that stable coherent emission has been observed.

Because the bunch length may be made smaller in a recirculated linac than the desired mimimum range, and because THz brilliance will be maximized by utilizing undulator emission, a device roughly as in Figure 1 makes an interesting THz source. Some beam parameters are listed in Table 1. A 300 keV beam of electrons of 100 ? A average current originates from a photocathode gun. (A thermionic gun, perhaps even without beam chopping may just as well be used in this application. A photocathode gun is assumed here only because the beam is naturally bunched from such a source; the emittance requirements are not so stringent as to require a photocathode gun electron source.) 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 turn-around "arc" is chosen to have the correct M_{56} to yield maximum bunching at the wiggler. After emitting coherent undulator radiation, the beam is directed back through the SRF cavity on a decelerating phase. The beam is dumped at low energy and low beam power.

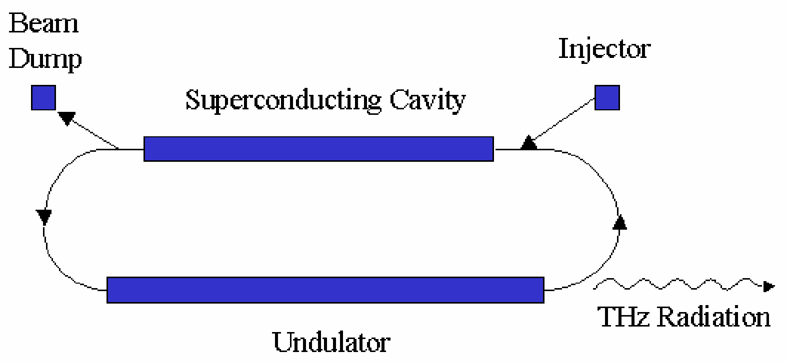

Figure 1. Compact High Average Power THz Source. The undulator is 1.25 m long in the case considered.

Table 1. THz Source Accelerator Parameters

Quantity	Value	Unit
Beam Energy	3.6-11.4	MeV
Average Beam Current	100	? A
Charge per Beam Bunch	14	pC
Bunch Repetition Rate	7.1	MHz
Normalized *rms* Beam Emittance	5	mm-mrad
Longitudinal *rms* Emittance	10	keV-degrees
rms Bunch Length at Wiggler	300 (90)	fsec (? m)

None of the parameters in Table 1 stretches 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 2 below. The CEBAF accelerator routinely accelerates average currents of order 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. A simple estimate gives the charge-per-bunch limit. If the beam is fully bunched longitudinally, the total energy of the coherent undulator emission, E_{cur}, is approximately

$$E_{cur} \approx N_e^2 \frac{2\pi}{6} \alpha N K^2 h \frac{c}{\lambda} = \frac{4\pi^2}{6} \frac{N_e^2 e^2}{\lambda} N K^2$$

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

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

The electron bunch energy is $E_{beam} = N_e \gamma mc^2$, and by requiring, conservatively, that $E_{cur} / E_{beam} \le 1/4N$, one obtains a bunch charge limit of

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

where r_e is the classical electron radius. For 1 THz emission from a 6.6 MeV beam driving a 25 period undulator, the maximum bunch charge is about 14 pC, and for a 3 period undulator the maximum bunch charge is almost a nanoCoulomb. In practice, emission at this maximum charge may be somewhat less than the estimate as the bunch may not be fully bunched longitudinally, especially at the high bunch charge corresponding to a small number of undulator periods. Also, it 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. By filling every possible accelerating phase in the accelerator with this maximum charge, one obtains an estimate of the "maximum" power possible in this type of device,

$$P_{cur} \approx f_{rf} \frac{3\alpha\left(1 + K^2/2\right)}{128\pi^3 N^3 K^2} h \frac{\lambda_0 c}{r_e^2}.$$

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.

For storage rings, assuming the same beam properties and the same average current, the total THz power cannot be 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. By assuming that the beam is "micro-bunched" at wavelength ? in a modulated Gaussian distribution with longitudinal extent ? ,

$$I(z) ? \frac{1 ? m}{\sqrt{2?}\,?}\exp\left[? z^2/2?^2\right] ? \qquad 0 ? m ? 1$$

$$\frac{m}{\sqrt{2?}\,?}\frac{1}{1 ? \exp\left[? 2?^2 ?^2/?^2\right]}\exp\left[? z^2/2?^2\right]\left[1 ? \cos\left(2? z/?\right)\right]$$

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

$$P_n ? 0.52\frac{N_e^2 e^2 c}{?^2} n^{1/3}\left|S(n?_0)\right|^2$$

where n is the harmonic number, ? is the bend radius, and $?_0 = c/?$ is the fundamental angular frequency of the revolution. Summing the form factor around $n_0 ? 2?\,?/?$, 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

$$E_{csr,microbunching} ? 3.25\frac{N_e^2 e^2}{?} n_0^{1/3}\frac{\sqrt{?}\,?}{?}\frac{m^2}{4} ?? E_{cur}.$$

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

In Table 1, the repetition rate has been chosen to provide a convenient and demonstrated average current to work with, 100 ?A, consistent with 14 pC derived above. It should be bourn in mind that an additional factor of 200 in average power is possible, if a 20 mA injector can be developed to fill every accelerating phase with 14 pC of bunch charge. Beam recirculation and beam energy recovery become essential in a device in such a parameter regime.

The beam quality figures in Table 1 are estimates based on measurements performed on the IR DEMO FEL at Jefferson Lab [17]. This device produced 7.5 mm-mrad normalized *rms* emittance and 30 keV-degrees longitudinal *rms* emittance at a bunch charge of 60 pC. Recent light source studies have numerical simulations of injector designs that perform considerably better in transverse normalized emittance: 1-2 mm-mrad at 77 pC bunch charge [19]. As can be demonstrated by a simple calculation, 10 keV-degrees longitudinal emittance is consistent with $?_E/E ? 1/4N ? 1\%$ and a bunch length of 90 ?m. To manipulate the longitudinal phase space in the needed way 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 degrees through the turn-around arc which has a bend radius of 20 cm and M_{56} of 63 cm. At this point in time, a linear design which shows adequate longitudinal optics exists; more detailed numerical studies which will lead to a better optimized injector should be performed. The dispersion at the undulator is 40 cm, a value that causes inconsequential growth of the spot size at the undulator. Only slightly more complicated beam optical designs for the recirculator can be used to suppress the dispersion if necessary.

Consistent with Table 1, some undulator parameters and photon beam characteristics are given in Table 2 for two cases of interest: first a few transverse oscillation period undulator which will yield a relatively wide-band 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 Eqn. 1 above. The fundamental flux into a bandwidth $?? /?$ is estimated as

$$F ? fN_e^2 \frac{?}{2} ? N \frac{??}{?} ?JJ?$$

where $?JJ?$ is a standard Bessel function factor which for $K ? 1$ is around 0.55 for fundamental emission. For 1 THz emission from a 6.6 MeV beam driving a 25 period undulator, the maximum bunch charge is about 14 pC, and for a 3 period undulator the maximum bunch charge is almost a nanoCoulomb. In practice, the emission at this maximum charge may be somewhat less than the estimate if the electron bunch duration is not smaller than $?$.

Finally, some care must be taken in evaluating the brilliance in the fundamental, as the parameter regime is somewhat different than is usual in X-ray production by undulators. A general estimate for the brilliance is [20]

$$B ? \frac{F}{?2? ?^2 \sqrt{?_r^2 ?? _x^2}\sqrt{?_{r'}^2 ?? _{x'}^2}\sqrt{?_r^2 ?? _y^2}\sqrt{?_{r'}^2 ?? _{y'}^2}}$$

where $?_r ? \sqrt{? N?_0 /4?}$, $?_{r'} ? \sqrt{? / N?_0}$, and the rest of the $?$ s are the transverse *rms* beam sizes and beam angular spreads at the undulator. Assuming a symmetrical $?$-function of 1 m at the middle of the undulator, and the emittance in Table 1, the *rms* beam sizes at the undulator are 0.62 mm and the angular spreads are 620 ? rad. Now $?_r$ = 1.5 mm and $?_{r'}$ = 15 mrad when N=25, and the brilliance is largely determined by the photon diffraction effects.

Table 2. THz Source Undulator and Calculated Optical Parameters

Quantity	Value	Unit
Undulator		
Period Length	5	cm
Period Number	3, 25	
Field Strength, K	1	
Wavelength at 6.6 MeV	0.3	mm
Fundamental Optical Power	0.8, 6.9	W
Fundamental Flux	$1.0?10^{18}$, $8.8?10^{18}$	photons/sec in 0.1% BW
Fundamental Brilliance	$1.9?10^{13}$, $3.3?10^{14}$	photons/(sec mm^2 $mrad^2$) in 0.1% BW
Optical Pulse Length ($N?$)	0.9, 7.5	mm

The average optical beam power is orders of magnitude beyond that available from other non-accelerator sources, is comparable to alternative accelerator driven sources which are physically much bigger, much more expensive, and require a much higher average beam current [21], and clearly superior to 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 3.6 and 11.4 MeV. Such changes are relatively easy to accomplish by: (1) scaling the magnetic fields in the recirculation system by the energy ratio, (2) adjusting the RF cavity operating amplitude down by the correct amount, and (3) 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. Storage rings are already used as IR sources, and it is natural to try to extend their performance into the longer FIR-THz wavelength regime. However, because of the demonstrated performance of Jefferson Lab’s IR DEMO device as a THz source [21], and because of the potential enhanced performance of the compact device described in this letter, it must be seriously questioned whether a storage ring approach is the right one. 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 [22]. It is true that the rings can carry more average current presently, but this advantage is offset considerably by the relatively long bunches and relatively small microbunching possible in rings.

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 letter, particularly in its low average current versions, has the potential to be an honest (relatively large!) table top device. One anticipates, because it is of relatively small size, that it might be built much less expensively than a whole storage ring.

In this paper we’ve presented a specific rendering of a compact THz source, and more importantly explored the physical limits of the use of small recirculating linacs for THz production. 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 ones 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. This work supported by the United States Department of Energy under Contract DE-AC05-84ER40150.

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