Compact Wideband THz Source

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Previously, I have published a paper describing compact THz radiation sources based on a single superconducting cavity and a relatively simple to design undulater [1]. In the paper, calculations were performed for either an $N = 3$ period undulater or an $N = 25$ period undulater, depending on the desired bandwidth of the radiation emitted from the source. Based on recent discussions and surveys of the emerging THz applications, it appears that a general purpose source designed to have a very wide bandwidth may be useful device. I have therefore recalculated the THz flux and power for a source with bandwidth at the extreme limit of an undulater designed with a single "½" period wiggle, augmented by bucking fields to reduce the deflection induced in the electrons by the undulater. The fluxes are comparable to the previous calculations, and sufficiently high that such a source is extremely attractive compared to alternative high average power sources. Parameters are given for a particular point design.

In the previous paper the THz radiation source is 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. 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. Beam energy recovery is not required in lower power versions of this device.

Because we intend to operate this device at relatively low average current to begin, and because of the increased complication attendant on closing the recirculation loop in the previous design, it was felt that it may be advantageous for the first prototype versions of the source to be built as simply as possible without recirculation. As this decision has relatively little impact on the performance characteristics of the source at low average current, I was asked to calculate and summarize the performance of a THz source laid out in an arrangement as in Figure. 1. The calculations follow from those in Reference 1 and will not be repeated in detail here.

Beam originates in a photocathode source and is soon thereafter bunched in a buncher. After being accelerated by a single superconducting cavity operated slightly off crest, the beam is further bunched in traversing a 180 degree bend. This bend could just as well be a small chicane so the whole device is on a line, at the cost of a higher magnet count total. The beam then passes through an undulater with parameters described below where the THz radiation is produced, and dumped in an electron beam dump.

Table 1 gives the accelerator parameters in our point design. The beam power is limited to 2.0 kW in our design to simplify the beam dump design. To increase the coherent THz emission from the bunch while keeping the magnetic field in the undulater at a moderate level, one would like the charge-per-bunch to be as large as possible. The charge-per-bunch is assumed to be 100 pC in our design. Such a charge-per-bunch has been demonstrated at the Jefferson Lab FEL to produce beam quality better than we need for our purposes, but if we increased this parameter to 1 nC, it might not be so promising to obtain the emittances we need from the source. Consistent with the beam power limitation and the beam energy choice made below, the repetition rate should be 2 MHz. The primary source of energy gain is a single superconducting cavity, operated in CW mode, which yields an energy gain in excess of 10 MeV.

The undulater design follows from one that I've recently filed a patent disclosure on. The beam orbit follows a path through the undulater of $x(z) = x_0 \exp\left(-z^2/2\sigma^2\right)$ by having the transverse magnetic field of $B(z) = B_{\max}\left(1 - z^2/\sigma^2\right)\exp\left(-z^2/2\sigma^2\right)$. Figure 2 shows the emitted THz spectrum at zero angle to the undulater axis for three values of the field strength in the undulater. At low field strengths the ½ power points for the spectrum are at the points 0.62 and 1.44 times the frequency of maximum emission. As the field strength increases the spectrum red-shifts, as is usual in conventional undulater theory, from the slowing down of the electron in the longitudinal direction as it enters the magnetic field. However, it is a good starting approximation to estimate the bandwidth using the low field strength values mentioned above. If one wishes to obtain substantial emission in the range between 480 micron (0.63 THz) and 200 micron (1.5 THz) one should plan to have the frequency of maximum emission at 1.5 THz/1.44, or about 1.0

THz. In terms of the scale length for the magnetic field σ, the maximum power is emitted at the frequency

$$\omega_{\max} = 2\pi f_{\max} = \frac{\sqrt{2}\beta c}{(1-\beta)\sigma} \approx \frac{\sqrt{2}2\gamma^2 c}{\sigma}$$

which has a wavelength

$$\lambda_{\max} = \frac{2\pi\sigma}{2^{3/2}\gamma^2}.$$

To get 1.0 THz with a σ of 4 cm (with the large pole in the undulater about 8 cm long) requires a beam γ of 17.2, or a beam energy of 8.8 MeV. In order to obtain a device that covers other frequency ranges, it is easy to change the range by changing σ and scaling the rest of the results properly. As suggested by A. Hutton, it may be advantageous to slightly modify the magnetic field so the undulater kicks the beam on purpose, allowing easy separation of the electron beam from the THz beam.

The total power may be estimated using a total energy sum rule, as applied to 1-D undulaters [2]

$$E_{CUR} \approx \frac{2}{3} N_e^2 e^2 \gamma^2 \int_{-\infty}^{\infty} \left(\frac{df}{dz} \right)^2 dz = \frac{\sqrt{\pi}}{2} N_e^2 e^2 \gamma^2 K^2 / \sigma = \frac{\sqrt{\pi}}{2} N_e \gamma K^2 \frac{r_e}{\sigma} E$$

where E_{CUR} is the energy emitted in coherent undulater radiation by a bunch of total energy $E = N_e \gamma mc^2$, N_e is the number of charges in the bunch, γ is the beam relativistic gamma, r_e is the classical electron radius, σ is the magnetic field scale length, and K gives the peak value of the magnetic field through the formula

$$K = \frac{eB_{\max}\sigma}{mc^2}.$$

We, conservatively given the FEL experience that allows greater outcoupling in the more difficult energy recovered arrangement, allow up to 0.5% of the beam energy to be converted into coherent THz undulater radiation. This yields the derived parameters in Table 2 given the assumptions made above.

The procedure that has been followed to effect the design actually has quite a bit of flexibility. For example, if it turns out that it is difficult to bunch 100 pC bunches adequately, it is possible to reduce the charge-per-bunch, increase the repetition rate, and increase the magnetic field in the undulater and still obtain THz power at the level indicated in Table 2. Also, I suspect that it will be possible to outcouple more than 0.5% of the beam power when there is no requirement for beam energy recovery. This leads to the possibility of significantly increasing the THz power beyond 10 W, or reducing the beam average current while retaining an average power of 10 W as indicated in Table 2. To explore such cases in detail requires calculating the full emission spectrum including radiation red-shifting at high field strengths, as indicated in Figure 2.

In conclusion, a small device including an electron source, a single superconducting cavity, and a small undulater can provide quite substantial THz beam power through the mechanism of emission of coherent undulater radiation. This work supported by the United States Department of Energy under Contract DE-AC05-84ER40150.

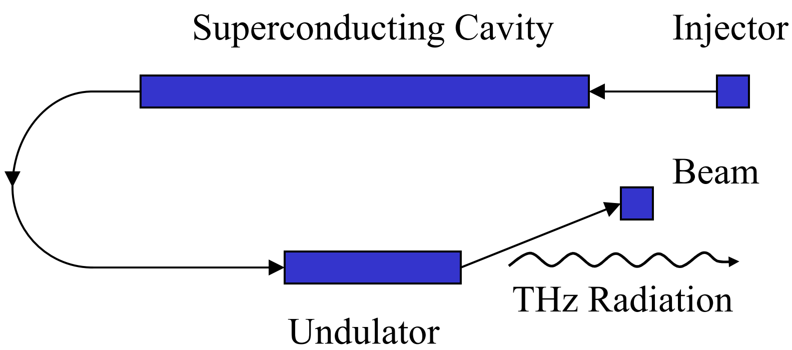

Figure 1. Compact High Average Power THz Source. The undulator is less than 30 cm long.

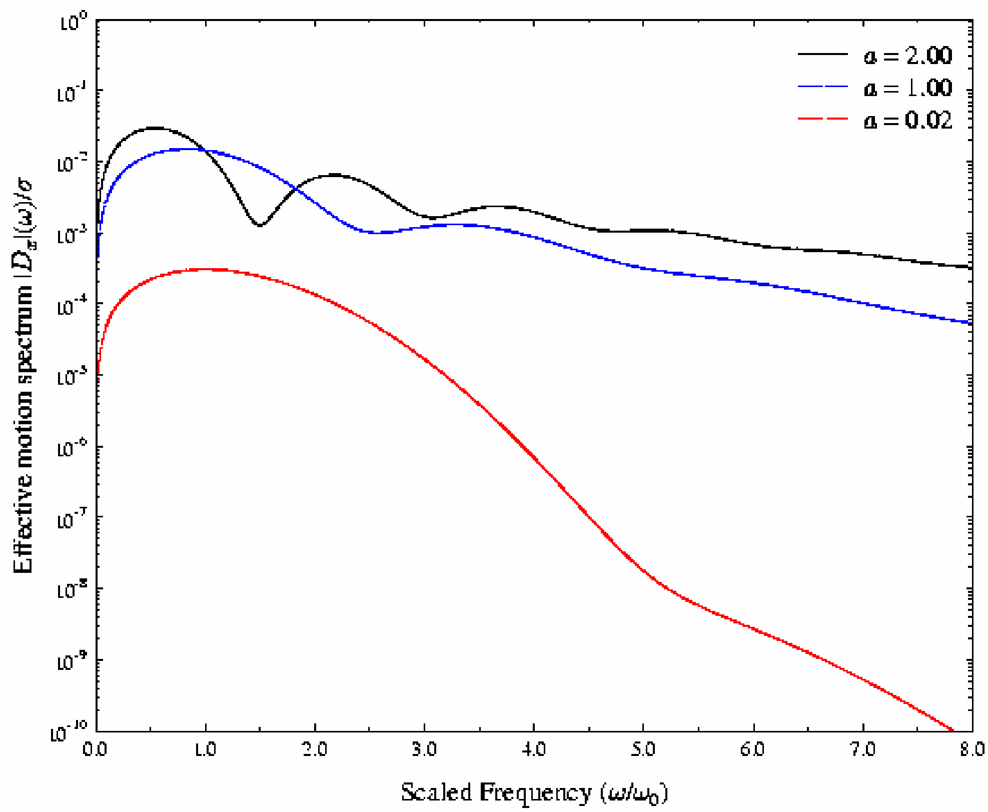

Figure 2. Scaled motion spectrum for wideband high average power THz source.

Table 1. THz Source Accelerator Parameters

Quantity	Value	Unit
Beam Energy	8.8	MeV
Average Beam Current	225	μA
Charge per Beam Bunch	100	pC
Bunch Repetition Rate	2.25	MHz
Normalized *rms* Beam Emittance	5	mm-mrad
Longitudinal *rms* Emittance	10	keV-degrees
rms Bunch Length at undulater	300 (90)	fsec (μm)

Table 2 THz Source Undulator and Calculated Optical Parameters

Quantity	Value	Unit
Undulator		
Length Parameter σ	4	cm
Wavelength of Maximum Power	0.3	mm
Maximum Field $B_{\max}$	1160	G
Field Strength, $K = eB_{\max}\sigma / mc^2$	2.7	
Fundamental Optical Power	10	W
Fundamental Flux at Max	1×10^{19}	photons/sec in 0.1% BW
Optical Pulse Length	80	μm

References

[1] G. A. Krafft, *Phys. Rev. ST-AB*, **7**, 060704 (2004)

[2] G. A. Krafft, D. Doryrin, and J. Rosenzweig, *Phys. Rev. E*, to be published