# TBONE: ULTRA-FAST HIGH-POWER COHERENT THz TO MID-IR RADIATION FACILITY

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*Abstract*

A linac based coherent radiation source in the THz to mid-IR range is proposed. The TBONE machine will deliver pulses of radiation as short as a few fs in the frequency range from 0.1 to 150 THz with up to MW peak power. This combination of parameters will open up unprecedented opportunities in THz and infrared applications, such as e.g. microscopy or spectroscopy. This paper presents the main parameters and design considerations. Emphasis is put on the study of suitable bunch compression and beam transport schemes.

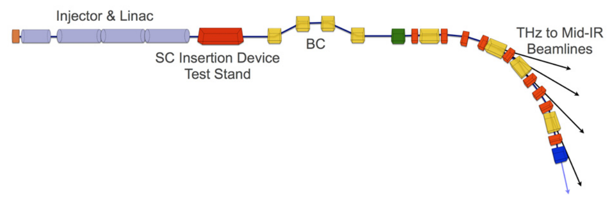


Figure 1: Sketch of the TBONE installation consisting of a linac, a bunch compression system and a magnetic lattice for the generation of coherent THz to mid-IR radiation. This sketch is based on one option for the design currently under discussion (lengths don't scale).

## INTRODUCTION

Questions of central importance in condensed matter science (such as superconductivity or behavior of correlated electron systems) as well as in biological applications (protein folding, solvation, biological interfaces) demand for an analysis within a wide spectral range from the THz region up to the IR. In contrast to the importance of this spectral region there is a lack of intense radiation sources, which cover the whole range. Therefore, research is split between communities that use short pulse lasers (in the IR via nonlinear optics, in the THz via photoconductive emitters), other table top sources (thermal radiators) and Free Electron Lasers. The latter deliver exceedingly high pulse energies at fixed wavelength (typical bandwidth 1%) with a tuneability that is strongly limited by the machine tuning. Consequently, spectroscopic applications are restricted.

The proposed light source will foster experiments which utilize the linear light-matter interaction that are presently limited by the available flux; methods which require a high penetration depth into absorbing matter, as in biological applications, are within this group. Ellipsometry is another case where the availability of intense and coherent radiation restricts the seamless determination of the full dielectric function, i.e. with real and imaginary parts over the entire IR/THz spectrum. By filling this gap, a broad description of the nature of elementary excitations and energy levels in superconductors, Mott insulators or charge density wave systems will be realized. Furthermore, the high average power of the source is of importance for lowering detection thresholds down to a single protein or to single nanoparticles or quantum dots. One candidate to achieve this goal is represented by the s-SNIM technique (scanning near field infrared microscopy).

In addition, TBONE will open up completely novel experiments which probe nonlinear interactions. The extremely short electron pulses will emit a transient electromagnetic half-cycle pulse of the same duration containing all the frequencies. This will allow ultrafast experiments with ultimate time resolution. Research in ultrafast science is an extremely active field, with an important community, where the extension of the techniques into the spectral region of TBONE will contribute strongly to its advancement.

## MAIN PARAMETERS

The accelerator parameters necessary to reach the science goals outlined in the previous section are listed in Tab. 1. To achieve as broad a spectral range as possible, the effective pulse length should be of the order of 5 fs for closing the gap to the well established near-IR to visible light technology. To keep a sufficiently high time averaged power for spectroscopic studies, the repetition rate needs to be higher than typical frequencies occurring in methodical routines, such as in scanning probe microscopes. The obvious choice of technology is therefore a superconducting electron linac. The TESLA SRF technology at 1300 MHz is well established and in use for many projects around the world (see, for example, [1]). For the generation of coherent radiation, a beam energy of about 60 MeV would

Table 1: TBONE design parameters

| | |
|---|---|
| Frequency Range | 0.1 - 150 THz |
| Peak Power | up to several MW |
| Pulse Length | down to 5 fs |
| Repetition Rate | 10 MHz |
| Linac Energy | 60 - 100 MeV |
| Bunch Charge | 10 - 100 pC |

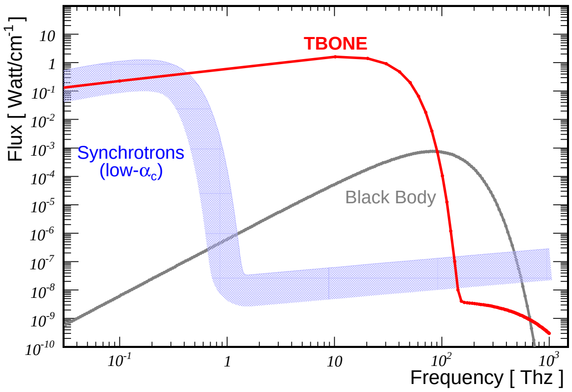


Figure 2: Time averaged power as a function of frequency as obtained from Eq.(1). The red curve shows the spectrum estimated for TBONE for beam energy of 100 MeV, a bending radius of 2 m and a bunch charge of 100 pC. The blue band indicates the range covered by storage rings operated in the low-$\alpha_C$ mode (see, e.g. [4,5]). All calculations were done for an aperture of 90×90 mrad.

suffice. Since TBONE could also serve as a test stand for superconducting insertion devices the option for an energy of 100 MeV should be kept. Bunch charges required range form 10 to 100 pC. For the TBONE set of parameters two options for an electron source are considered: a DC photo emission gun (e.g. [2]) or an SRF photo injector (e.g. [3])

Based on the parameters of Tab. 1 the spectral power density was calculated for TBONE. Following the calculations and reasoning in [6–8], the time averaged spectral power density for the $N$ electrons of a beam with current $I$ can be expressed as

$$\frac{dP}{d\omega} = \frac{9\rho}{16\pi^3 c\gamma^2} P_{\text{total}} \left((1-\mathcal{F}) + N\mathcal{F}\right) \; \phi_{\max} \, \mathcal{I}(\theta_{\max}) \tag{1}$$

where $\phi_{\max}$ and $\theta_{\max}$ are the horizontal and vertical opening angles, respectively and $\rho$ is the bending radius. The

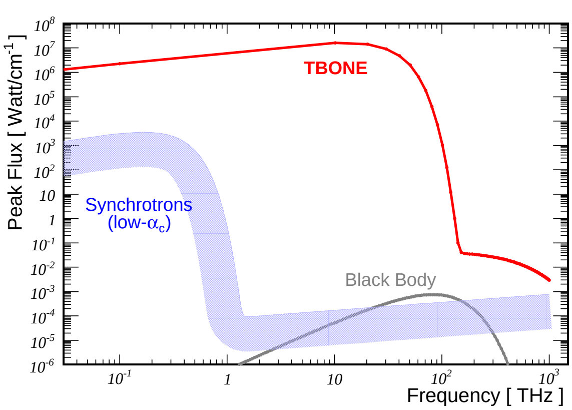


Figure 3: Peak power as a function of frequency. The red curve shows the spectrum estimated for TBONE for beam energy of 100 MeV, a bending radius of 2 m and a bunch charge of 100 pC. The blue band indicates the range covered by storage rings operated in the low-$\alpha_C$ mode. All calculations were done for an aperture of 90×90 mrad.

total (incoherent) power emitted by the $N$ electrons is

$$P_{\text{total}} = \frac{e\gamma^4 I}{3\epsilon_0 \rho} = 88.46 \, \frac{E^4 I}{\rho} \tag{2}$$

in units of kW for the electron energy $E$ in GeV, the current in A and $\rho$ in m; the form factor for a Gaussian charge distribution is given by $\mathcal{F} = e^{-(\frac{\sigma\omega}{c})^2}$. $\mathcal{I}$ represents the integral over $\theta$ and $\phi$ of the function

$$F(\theta) = (1+\gamma^2\theta^2)^2 K^2_{2/3}(G) \left[1 + \frac{\gamma^2\theta^2}{(1+\gamma^2\theta^2)} \frac{K^2_{1/3}(G)}{K^2_{2/3}(G)}\right] \tag{3}$$

with $G = \frac{\omega}{2\omega_c}\,(1+\gamma^2\theta^2)^{3/2}$ and $K_{1/3,2/3}$ the modified Bessel functions. The spectral power density for TBONE shown in Fig. 2 was calculated for a beam energy of 100 MeV, a bending radius of 2 m and a bunch charge of 100 pC.For the aperture $\theta_{\max} = \phi_{\max} = 90$ mrad was assumed. An equivalent Gaussian bunch length of 5 fs was used. As will be shown later, the overall bunch shape is not Gaussian. However, the extension of the spectrum to high frequencies is dominated by the sharpest feature of the distribution. Therefore an approximation by an effective Gaussian describing the dominant feature is in order. Attention must be paid to the fact that, depending on the exact shape of the bunch, the peak current and therefore the power will be reduced. The blue band indicates the typical range covered by storage rings operated in the low-$\alpha_C$ mode (see, e.g. [4, 5]). The peak powers displayed in Fig. 3 are related to the time averaged power with $P_{\text{ave}} = P_{\text{peak}} T f_{\text{rep}}$ where $T = 2\sigma$ is the pulse duration and $f_{\text{rep}}$ is the repetition rate.

## BEAM OPTICS CONSIDERATIONS

Since the spectrum of the emitted coherent radiation depends largely upon the exact bunch shape, the bunch compression and beam transport scheme is very important. The design studies done up to present have therefore been focused on the beam optics. It is important to note that the ultra-short feature dominant in the coherent emission does not need to be Gaussian. A short sharp spike with long tail would mainly result in reduced values for the peak power which in our case is regarded as less critical. First studies with the TBONE parameter set are presented in the following. As a next step more detailed studies with a fully matched transport system and a simulation of the linac are required. In addition studies of alternative compression systems (single and multi-stage) and transport structures are foreseen.

As one option for the bunch compression in TBONE, a 4-dipole magnetic chicane bunch compressor was considered. The distance between bends 2 and 3 is 1.14 m, between bends 1,2 and 3,4 is 2.5 m and the overall length is 8.14 m. One bend is 0.5 m long. The simulations were performed with the program CSRtrack [12]. The initial distribution used in the example of Fig. 4 and Fig. 5 was generated to match the shape of the charge distribution at

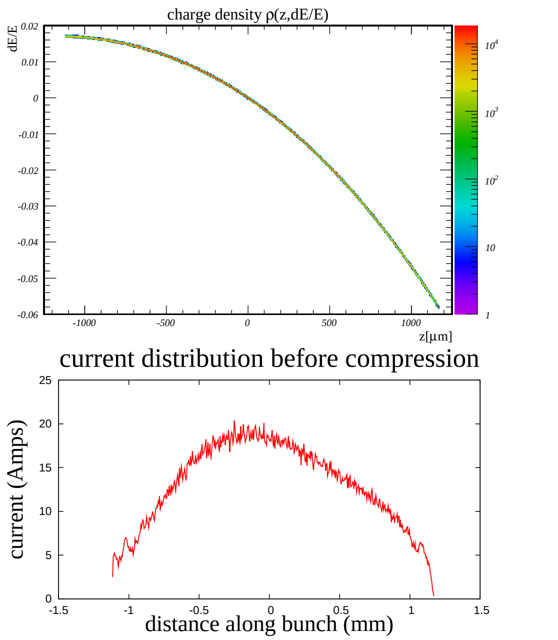


Figure 4: Longitudinal phase space (top) and current distribution (bottom) at the entry of the bunch compressor.

FERMI's bunch compressor [9]. Bunch charge and length were adjusted to TBONE parameters. The final distribution at the exit of the bunch compressor shows a current spike with a 5 fs RMS width. CSR effects are not apparent in the simulations. A comparable compression was reported for the first LCLS bunch compressor chicane [10].

To limit the divergence of the beam after the extreme compression the transport system should have active compression capabilities or be at least isochronous. One option could be a so-called "missing bend arc" [11] shown in Fig. 6 which allows for a very flexible adjustment of longitudinal compression or expansion.

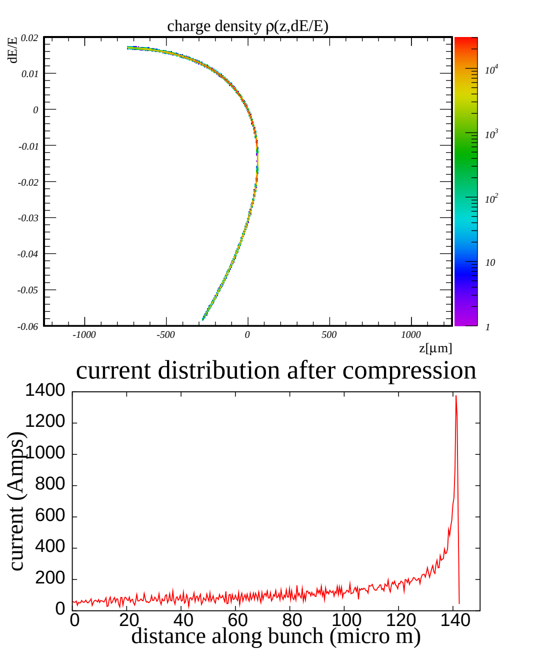


Figure 5: Longitudinal phase space (top) and current distribution (bottom) at the exit of the bunch compressor sporting a sharp spike of 5 fs RMS with a long tail.

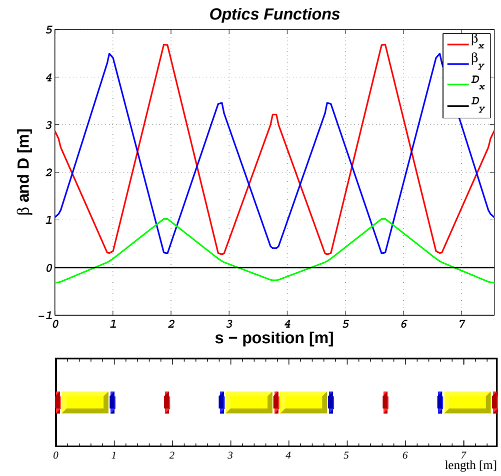


Figure 6: Top: Optics functions for a missing bend FODO structure that could be used as a beam transport system. Bottom: Magnetic elements of the structure; dipoles are drawn in yellow, quadrupoles in red or blue.

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