CONCEPTUAL DESIGN OF A THZ FACILITY AT THE ELBE RADIATION SOURCE

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Abstract

To extend the wavelength range of possible experiments from the FIR into the THz region a dedicated beamline is planned at the ELBE Radiation Source. The beamline will deliver coherent transition radiation and coherent synchrotron radiation as broad-band (essentially single-cycle) radiation. Superradiant undulator radiation will be produced for a tunable narrow-band radiation source in the 100 GHz to 3 THz range. This requires a compression of the ELBE electron beam down to 160 fs bunchlength. The beam transport and bunch compression scheme as well as the properties of the produced radiation are presented in detail.

INTRODUCTION

At Forschungszentrum Dresden-Rossendorf, Germany, the radiation source ELBE (Electron Linac with high Brilliance and low Emittance) operates on the basis of a superconducting linear accelerator for electron energies up to 40 MeV with an average beam current of 1 mA in quasi continuous wave (cw) mode. The electron linac serves as a driver to generate several kinds of secondary radiation and particle beams. Two free-electron lasers generate radiation in the mid and far infrared for a very large field of applications reaching from semiconductor physics to biology. The success of the facility leads to an ever increasing demand by the users. Of particular interest are longer wavelengths than provided now by the FIR FEL [1] (max. $\approx$250 μm) bridging the THz "gap" and also extremely short pulses (ideally single-cycle waveforms) of broad-band radiation. While broadband THz radiation can be produced by thermal sources and, more recently, by semiconductor and high-power laser driven sources both the average and peak power of such sources are vey limited. The idea of the facility planned at ELBE is to produce high-power THz radiation from sub-picosecond electron bunches of high bunch charge (compare [2]). Electron bunches delivered by the ELBE accelerator can be compressed to less than 200 fs buchlength and will radiate coherently up to 3 THz or down to 100 μm wavelength.

FACILITY OVERVIEW

Fig. 1 shows an overview drawing of the facility to illustrate the setup. A magnetic chicane is used to bunch-compress a chirped beam delivered by the ELBE accelerator (from the left-hand side in the figure). The chicane is immediately followed by a vacuum cross which allows different radiators to be used.

A mirror placed at the left-hand side of the beam (upper side in the figure) reflects dipole radiation form the final chicane magnet into the radiation transport beamline. The spectral power distribution of this source is shown in Fig. 2. With the presently available ELBE beam of 77 pC bunch charge at 13 MHz repetition rate the total radiation power will be $\approx$5 W into an acceptance angle of 60 mrad of the optical beam transport system assuming a bunch compression to 160 fs. Alternatively, a transition radiation screen can be inserted into the beam, primarily, for diagnostics but as a source of THz radiation with lowered average beam current as well. The visible part of the transition radiation can be viewed with a CCD camera via a mirror insertable into the THz beam path in order to characterize the electron beam spot. An edge radiator could be inserted if this port is to be used as a non-destructive pickup for timing or diagnostic purposes while running the wiggler source. All these sources deliver essentially single-cycle broad-band radiation which is only limited by the bunchlength on the high-frequency side and the acceptance of the optical beam transport on the long-wavelength side.

As a source of narrow-band THz radiation a wiggler with 30 cm period length is foreseen. The coherent superposition of the resulting source terms leads to a spectrally narrow and extremely intense THz beam which can be regarded as superradiance. Note that this does not require an optical resonator like in an FEL an thus, such a source can be operated at any repetition rate. With beam energies ranging from 15 to 35 MeV and wiggler strengths running up to K_{rms}=5 (see Fig. 3) the wavelength range from 100 μm up to $\geq$3 mm can be covered. The spectral width is of the order of the inverse number of wiggler periods which places this source between broad-band sources and an FEL. One should be aware, though, that odd higher harmonics of the desired radiation will always be present and can only partly be subdued by chosing an optimum bunchlength.

After the chicane a magnetic quadrupole triplet focuses and matches the electron beam into the wiggler. To account for the dispersion of the wiggler, the bunch compression has to be tuned for a slight under-compression. The time-focus, i.e. the shortest bunchlength should be placed at the center of the wiggler. The wiggler dispersion also limits the number of wiggler periods which can be utilized for coherent emission. This limitation is the main reason

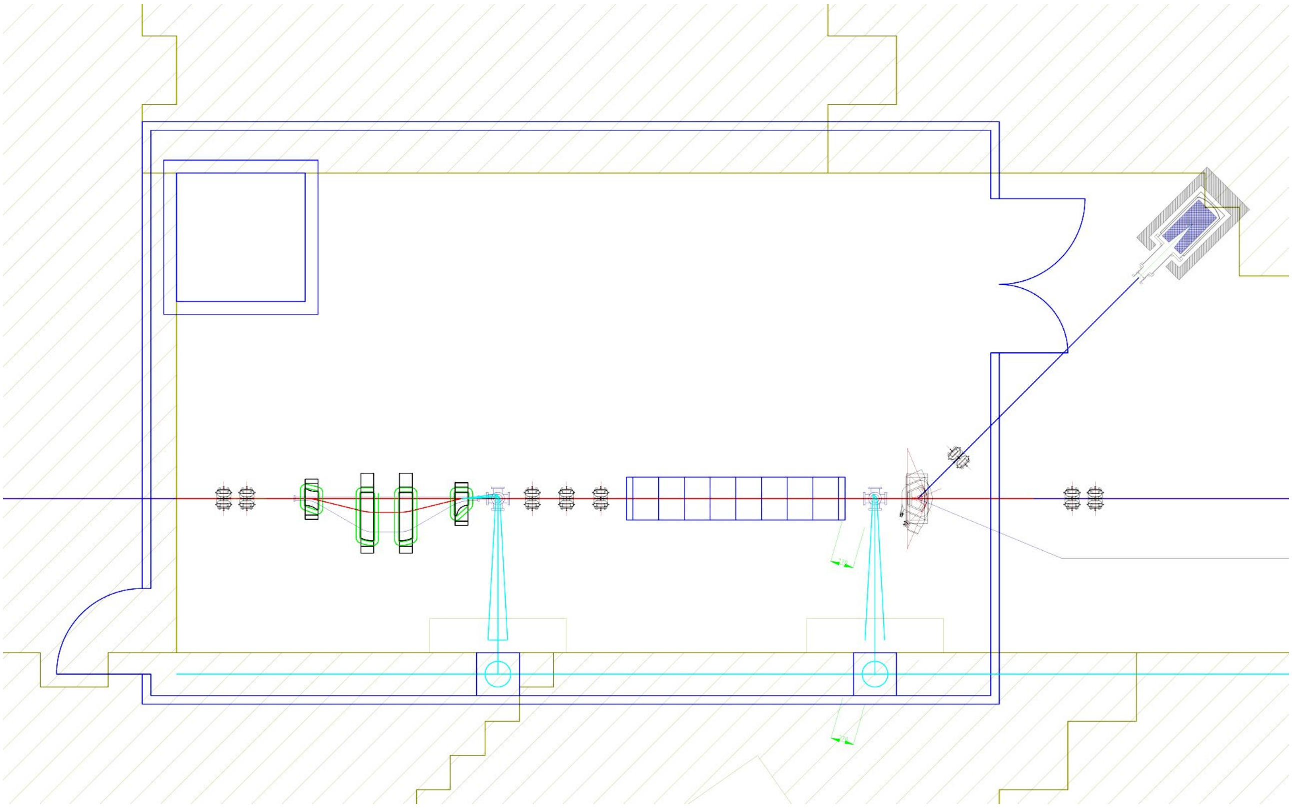

Figure 1: Preliminary drawing of the beamlines of the THz facility showing the magnetic chicane for bunch comression and the wiggler along with the necessary focussing qudrupoles and deflecting dipoles. The outline of the THz laboratory on the rooftop of the accelerator vault is shown in dark blue. The projected optical beam transport path ist sketched in cyan.

for us to chose a low count of only 8 wiggler periods plus end-pieces. The wiggler radiation is reflected into the optical beam transport line with a hole-mirror which allows the electron beam to pass through. The electron beam given by the wiggler matching has a very low cross section at this place. Therefore, placing the mirror before the bending dipole allows the highest acceptance of the optical beam transport. This also eliminates the dipole radiation from the optical beam. During tuning visible transition radiation from the mirror can be imaged to ensure a proper electron beam transport through the hole. After the mirror the electron beam is deflected into the beam dump with a dipole and a quadrupole focussing in the dispersive plane of the dipole.

The THz laboratory will be built on top of the radiation shielding ceiling of the accelerator vault. It's extensions are drawn in Fig. 1 in blue. It will be setup on a separate concrete base which is to some extent vibration decoupled from the accelerator shielding. Also, the optical beamlines will have no mounting to the shielding walls but will be supported from the accelerator foundation and the laboratory base, only.

While the optical beam transport is not yet designed in detail the general outline is quite clear. There will be two beamlines with almost identical design from the radiation cave up to the laboratory. From all sources, the radiation is reflected horizontally to the right-hand side of the electron beam. At short distance a focussing mirror deflects the beam upwards focussing it onto the vacuum window separating the accelerator vacuum from the optical beam transport line. Near the ceiling of the accelerator vault the beam is again deflected with a focussing mirror back to the original direction into the radiation shielding wall. Inside the wall a (probably flat) mirror deflects the beam upwards into the THz laboratory where it will emerge near the wall and can be redirected and focussed as required by the experimental setup. This dog-leg design of the optical beam transport is dictated by radiation shielding requirements. Thats why, at least one connection to the mirror chamber for the upward beam deflection has to be made inside the wall. To ease this mounting the beamline channel has been placed right at the surface of the original shielding wall. An additional radiation shielding closing the remaining direct line-of-sight will be installed after mounting the beamlines. The channels have been sized to accomodate at least 250 mm beam tubes with the according flanges and mirror chambers.

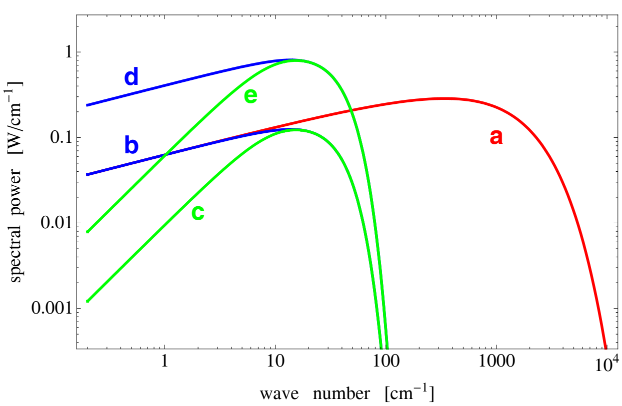

Figure 2: Spectral power density of coherent synchrotron radiation from a 40 MeV electron beam in a ρ=1 m bending dipole into a (60 mrad)^2 acceptance angle – **a** from a point charge with Q=77 pC at 13 MHz repetition rate, **b** and **c** from bunches of 150 fs (r.m.s.) bunch length with 77 pC, **d** and **e** from 1 nC bunches with 500 kHz repetition rate. Curves **c** and **e** include diffraction losses due to the limited source size in a 40 mm high vacuum chamber.

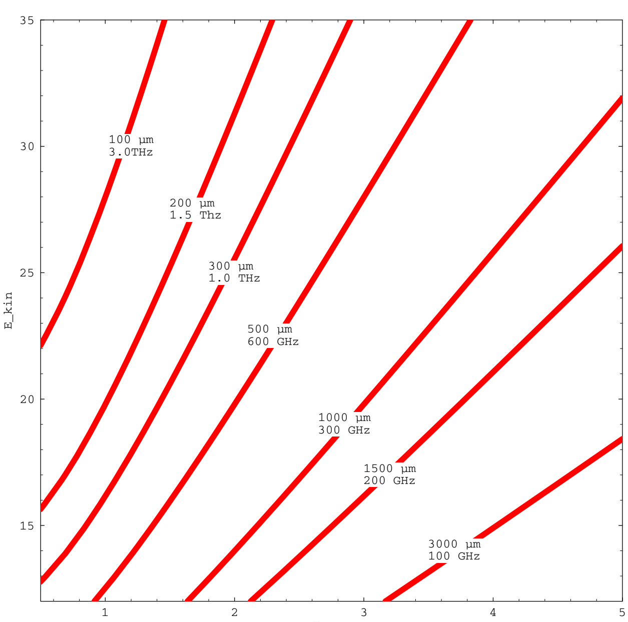

Figure 3: Tuning range of a 30 cm period length wiggler at ELBE beam energies.

BUNCH COMPRESSION

A conservative approach to the simulation of the bunch compression system starts with the 77pC beam delivered by the ELBE thermionic gun. This beam is well characterized and has been used in routine user operation for several years now. In future the superconducting RF photo-gun under commissioning will deliver 1nC bunch charge with similar characteristics of the longitudinal phase space, so, it should be possible to transfer the simulation results that were obtained for the thermionic gun.

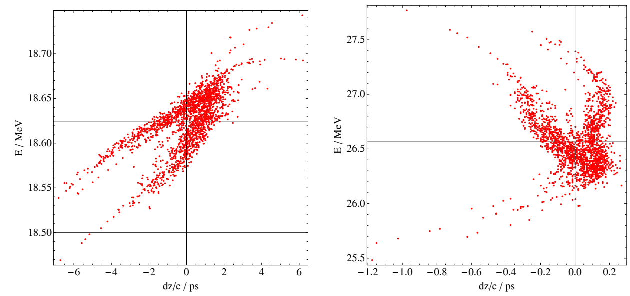

Figure 4: Longitudinal phase space of the electron beam after the first linac (left) and after bunch compression (right). Note the different energy spread and time scales.

The details of the capture process into the first accelerating cavity are dominated by the relatively low inital beam energy of 250 keV and the maximum achievable accelerating gradient of 10 MV/m for our cavities. The beam has to be injected as much as possible ahead of the accelerating field crest due to the low inital β. In fact, if one optimizes for lowest emittance one even injects into a just decelerating phase. Still, the beam is not accelerated fast enough to stay on the crest of the accelerating field but slips behind in the first few cells. This way, in the last cells of the first cavity the beam acquires a considerable chirp with the head of the bunch having higher energy than the tail (see Fig. 4 left-hand panel). In all subsequent cavities the beam has $\beta\approx$1 and the phase can be adjusted at will. At the exit of the first linac the bunchlength is somewhat below 2 ps (rms) with an energy spread less than 100 keV total. The simulations yield longitudinal emittances of $\approx$40 keV ps – similar values have been measured but at lower bunch charge, only.

For bunch compression with a magnetic chicane one now has to modulate a sufficient chirp onto the beam. A desired bunchlength of 150 fs (rms) will require at least an energy spread of 260 keV (rms). However, the modulation that can be imposed with the second accelerator module of ELBE is limited to $\sim$100 keV/ps and it has to reverse the existing correlation, too. Therefore, we will use the existing chicane in between our two accelerator modules to stretch the bunch to $\sim$3 ps what then allows to sufficiently chirp the beam with the second module. The start-to-end beam transport has been simulated using PARMELA which yields an (rms) bunchlength of 160 fs. It is desirable, to operate the second cryomodule close to the zero-crossing of the accelerating field as this minimizes the third-order distortions of the longitudinal phase space. This has to be traded off to the achievable final energy. In Fig. 4 (right-hand panel) a case is shown where the second cryomodule is still accelerating by 8 MeV, the according distorsion is clearly visible. While the relative energy spread of this beam is huge ($\sigma_E/E>$1%) the beam could still be transported and bunch-compressed with only slightly increasig the longitudinal emittance (by about 10%). The bunch compression in the final chicane has been checked with CSRtrack for emittance degradation due to coherent synchrotron radiation. The effect on the bunch shape is marginal with the majority of the particles loosing only 20-40 keV into synchrotron radiation. The beam transport also surprisingly well agrees with a simple first-order description.

THE THZ EXPERIMENTAL AREA

For experiments using these new THz sources, a dedicated laboratory platform will be necessary, which has to be as close to the THz generation as possible. To this end, we intend to set up the THz beamline in vertical direction and to establish a laboratory room (Fig. 5) right above the accelerator cave.

The laboratory will be equipped with a vacuum Fourier-transform spectrometer (FTIR). The broadband THz radiation will be used as a source for the FTIR, providing orders of magnitude higher power than the notoriously weak Hg-lamp that is normally used. Furthermore, the FTIR can be used for chemical imaging in the THz range with a dramatically increased signal-to-noise ratio. This will result in short measurement times when scanning the beam across the sample for recording images. The NIR radiation from a regenerative amplifier can be applied for exciting carriers in undoped samples and measuring the spectral response in the THz range. Tuning the delay between the NIR pulse and the THz pulse will even allow temporal resolution in these experiments.

Permanently installed experimental setups will include near-field microscopy and time resolved measurements. Setups will be available where the beam from the new THz sources is used as both the pump and the probe beam (single-color pump-probe spectroscopy). When the broadband source is applied either the pump, or the probe beam can be spectrally filtered according to the demand of the experiment. Additionally there will be the possibility to use radiation in the near infrared range from a regenerative amplifier system either as a pump beam or as a probe beam (two-color pump-probe spectroscopy). This is particularly interesting, since the pulse repetition rate (a few 100 kHz) matches very well the bunch repetition rate of the new sources. For phase-resolved characterization of the THz fields a modelocked femtosecond tabletop laser is foreseen which will be synchronized to the accelerator beam. The lab will provide space also for new experiments and installations on breadboards brought in by external users.

The great success of the experiments performed with the ELBE IR beams in high magnetic fields [3, 4] stimulate the interest in extending those experiments towards longer wavelengths. Unfortunately, the present transfer beamline from the free-electron lasers into the high-magnetic-field laboratory was designed for wavelengths up to 150 μm, only. Even though we have operated this transfer line with 250 μm beams, the losses are substantial and an extension

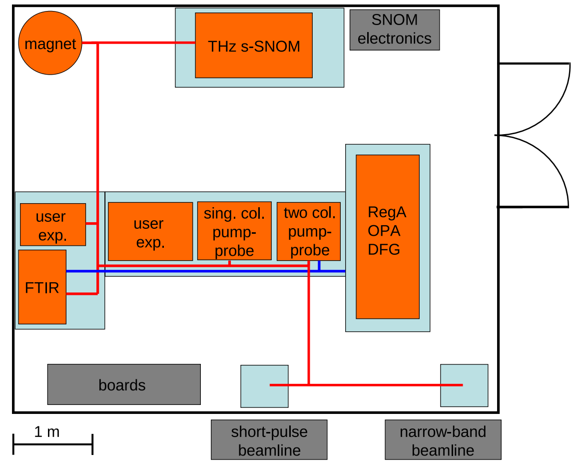

Figure 5: Projected layout of the THz optical laboratory.

towards longer wavelengths seems problematic. For this reason it was decided to install a superconducting magnet for fields up to 16–18 T right at the new THz facility. The magnet will be installed in a pit beneath the optical laboratory reaching into the accelerator vault. The projected position is shown in the upper left-hand corner of Fig. 1, the necessary additional concrete radiation shielding is not shown. The magnet will contain a detector (bolometer) at the bottom, thus enabling THz magnetospectroscopy of semiconductor nanostructures and correlated electron systems in high magnetic fields.

OUTLOOK

With the funding available, the construction work for the new laboratory already has started. The installation of all major components and running first beams is planned for year 2012.

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