BEAM STUDIES FOR TBONE

Steffen Hillenbrand, Miriam Fitterer, Nicole Hiller, André Hofmann, Erhard Huttel, Vitali Judin,
Marit Klein, Sebastian Marsching, Anke-Susanne Müller, Kiran G. Sonnad[*], Pedro Tavares[†],
KIT, Karlsruhe, Germany

Abstract

The Karlsruhe Institute of Technology (KIT) proposes to build a new light source called TBONE (**T**Hz **B**eam **O**ptics for **N**ew **E**xperiments), which aims at a spectral range of 0.1 to 150 THz with a peak power of several MW and a pulse length of only 5 fs. In order to achieve this, a beam transport system with minimal losses and a high bunch compression is required. In this paper we present the beam dynamics simulations of the superconducting (SC) linac as well as of the bunch compressor and give a short status report of the TBONE project.

INTRODUCTION

Many important questions from solid state physics to biological applications demand an analysis within a wide spectral range from THz to IR. Despite the importance of this spectral range, there is a lack of sources that can cover it with high intensity. Therefore the KIT proposes to build a new, linac-based broadband synchrotron radiation facility dedicated to the production of coherent THz to mid-IR radiation called TBONE. It will consist of a superconducting linac, a bunch compressor and a magnetic lattice in which the coherent radiation will be generated as edge radiation. The key idea is to compress the bunch length to below the wavelength of the desired radiation to get coherent amplification of the emitted power for these wavelengths. For TBONE this means reducing the effective bunch length to 5 fs in order to achieve the spectral range required for user experiments. Since the length of the radiated pulse is directly linked to the length of the electron bunch this also gives the time resolution. The design parameters of the planned facility are given in table 1, the conceptual layout is shown in Fig. 1. Further information about the project can be found in [1].

Table 1: TBONE Design Parameters

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

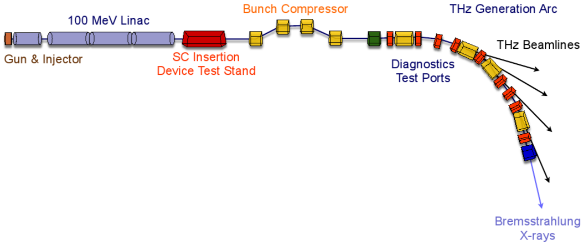

Figure 1: The conceptual layout of the TBONE facility, consisting of a SC linac, a bunch compression system and a magnet lattice for the generation of coherent THz to mid-IR radiation. (Lengths not to scale)

SIMULATION OF THE LINAC

The electron gun and injector for TBONE need to be matched to the overall performance requirements. This means they have to deliver charges of up to 100 pC with a repetition rate of about 10 MHz. Such systems are currently under construction in several places, e.g. [2, 3]. For the simulations presented in this paper, an initial distribution modeled after [2] was used. In order to meet the requirements for TBONE, two modifications had to be carried out: the bunch length was shortened by a factor of two and the phase space distribution was rotated, so that the twiss parameter α is equal to 0. A non-zero α would lead to an increase of the beam size as the linac does not include any focusing elements and a shorter bunch length is required to achieve the design bunch length of 5 fs at the end of the chicane. A shorter initial bunch length can probably be obtained by choosing a different phase of the injector booster cavity and a better adaption of the laser driving the photoinjector gun. The assumed energy and particle distribution after the injector are shown in Fig. 2, the parameters are listed in table 2. The injector is followed by a SC linac consisting of three 9-cell Tesla type cavities operated at a fundamental frequency of 1.3 GHz. The beam dynamics of the SC linac were simulated with PLACET, which includes the simulation of RF and wakefield kicks in the cavities [6]. Further simulations with the halo and tail generation package HTGEN [4] in combination with PLACET (PLACET-HTGEN) and analytical estimates showed, that no significant losses are to be expected due to halo and tail generation [5].

PHASE OPTIMIZATION AND BUNCH COMPRESSION

For the magnetic bunch compression a linear energy chirp (correlation between particle energy and position in

---

[*] Now at Cornell University
[†] On leave from LNLS, Campinas

Table 2: Used Beam Parameters before and after the Linac

		Initial	5-20-20	5-30-30	5-40-40
$\epsilon_{x,y,N}$	[μm]	1.40	1.40	1.40	1.40
σ_z	[ps]	2.06	2.06	2.06	2.06
E	[MeV]	8.35	73.9	70.6	66.0
Q_{bunch}	[pC]	83.86	83.86	83.86	83.86

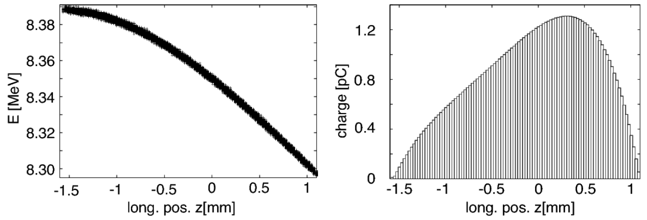

Figure 2: Energy and particle distribution at injection in the SC linac

bunch) along the bunch is desired. It is introduced in the injector and reinforced in the linac by running all three cavities above transition. The first cavity mainly accelerates, while the second and third cavity are responsible for the chirp. While a higher phase increases the chirp, it also reduces the beam energy. Therefore a compromise has to be found. Fig. 3 shows the energy distributions after the SC linac for different phases in cavities two and three. The longitudinal particle distribution does not change along the linac. The resulting particle distribution has been tracked through the compressor chicane using the Accelerator Toolbox for Matlab [8]. To achieve maximum compression the bending radius of the magnets, their length and the length of the outer drift spaces have been optimized using Monte Carlo simulations. The results for the three different studied cases can be seen in Fig. 4. They show that for a linac phase of 20° a compression in the right order of magnitude can be achieved. With an increase of the phase to 30° the peak width and the peak current can be further improved, whereas a further increase of phase does not bring any advantages.

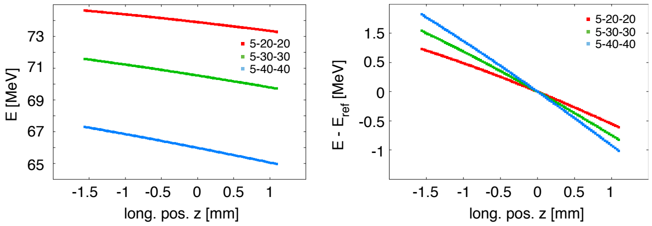

Figure 3: Left: Energy distribution after the SC linac - the beam energy decreases with increasing phase. Right: Energy distribution shifted by corresponding reference energy - a higher phase results in a stronger energy chirp. The legend is the phase in the 1st, 2nd and 3rd cavity.

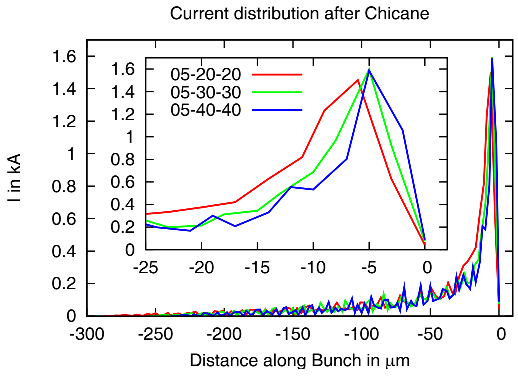

Figure 4: The achievable compression depending on the linac phase was studied. The inner figure is a zoom on the peak.

BUNCH COMPRESSOR

For the bunch compressor systematic studies have been carried out using CSRtrack [7]. In those simulations a linear chirp and a parabolic charge distribution were used. The starting values at the entrance of the chicane are given in table 3. The geometrical dimensions used for the simulations are given in table 4. For the charge, the highest design value was chosen for the simulations, the correlated energy spread is in the range given by [9, 10].

Table 3: Used Beam Parameters before Chicane

RMS bunch length σ_z	2 ps
Bunch charge Q_{bunch}	100 pC
Average beam energy E	100 MeV
Corroleted energy spread σ_E	1.93%
Normalized horizontal emittance $\epsilon_{x,N}$	2.0 mm·mrad
Horizontal beta	42.755 m

Table 4: Geometrical Dimensions of the Compressor

Length of dipoles	0.5 m
Length of outer drift spaces	2.5 m
Length of inner drift space	1.0 m

CSR Effects in Compressor

One of the key questions concerning the bunch compressor was the possible detrimental effect of coherent synchrotron radiation (CSR) generated in the magnets of the chicane on the charge distribution. To study this, the bunch charge was varied and the change in the current distribution was observed. (The power of the emitted coherent radiation depends quadratically on the charge.) The simulations indicate that CSR effects are not relevant for bunch charges below 1 nC, which is 10 times higher then the planned bunch charge for TBONE. It is therefore safe to assume that CSR effects in the chicane will not be a problem. To confirm

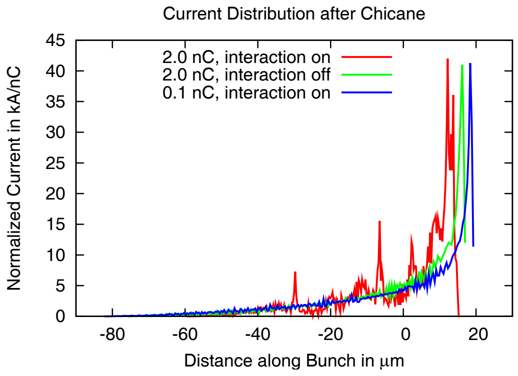

Figure 5: The influence of CSR on the current distribution was studied. CSR effects become relevant for a bunch charge of about 1 nC. Shown are the resulting current distributions for high and low bunch charge. For high charge a structuring of the distribution can be observed. This problem does not occur for the charge planned for TBONE. The current distributions are normalized to the corresponding bunch charge.

that the structuring is due to radiation all such interactions have been switched off, in which case the structuring vanished. The resulting current distributions with and without the effect of CSR can be seen in Fig. 5.

Lengthening After Chicane

Since the peak in the current distribution after the chicane is extremely short, space charge effects and different particle velocities might lengthen it very fast and therefore make the compression pointless and TBONE impossible. (The difference in velocity for two particles with 99 MeV and 101 MeV is about 150 m/s, creating a run time difference of 3.5 fs in a 2 m drift space.) To estimate the effects, drift spaces have been appended to the chicane and the change in the resulting current distribution has been observed. The results are visualized in Fig. 6. They show that for drift lengths of 10 m or less the peak changes its shape slightly, but neither does it lengthen nor does the peak current decrease significantly. Even for a drift of 15 m the peak remains pretty high and sharp. This has two reasons. The first reason is that, due to the initially parabolic current distribution, most of the particles contributing to the peak come from the initial center of the bunch. Therefore the energy spread within the peak is way lower then the energy spread of the whole bunch ($\sigma_{E,Peak} \approx \frac{1}{4} \cdot \sigma_{E,Bunch}$), leading to smaller differences in the particle velocities. The second reason is that right after the chicane the particles with higher energies are still at the tail of the current peak, meaning that they first have to overtake the leading particles before they can run off (This takes about 10 m for the correlated energy spread currently planned). During this process they still contribute to the peak current.

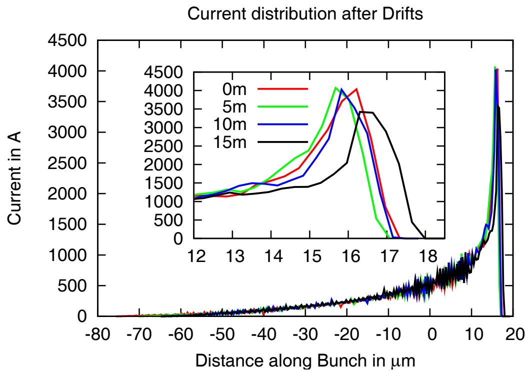

Figure 6: The broadening of the current peak after the chicane was studied. For that purpose drift spaces of varying length were appended to the chicane. The simulations indicate that the peak retains its shape longer then needed for TBONE. The inner figure is a zoom on the peak.

SUMMARY AND OUTLOOK

So far, studies of the bunch compression scheme and the linac have been performed with encouraging results. Within these studies it was confirmed that the uncorrelated energy spread of the beam must be as low as possible in order to achieve an extremely short effective bunch length. Studies on potential sources have started and will take this into account. Also, the possibility of a test stand for the bunch compression scheme is being investigated. The call for scientific applications has been issued.

REFERENCES

[1] Anke-Susanne Müller et al. "TBONE: Ultra-Fast High-Power Coherent THz to Mid-IR Radiation Facility", PAC '09

[2] C. Gerth and F.E. Hannon, "Injector design for the 4GLS energy recovery linac prototype", EPAC'04

[3] J. Teichert et al., "Results of beam parameter measurement of the ELBE electron accelerator after commissioning", EPAC'04

[4] H. Burkhardt et al., "Halo and Tail generator package HTGEN",

[5] M. Fitterer, "Modelling of Halo and Tail Generation in Electron Beams" , thesis, 2009

[6] D. Schulte, E. Adli, H. Burkhardt, B. Dalena, P. Eliasson and A. Latina "The Tracking Code PLACET", Manual

[7] M. Dohlus et al., "CSRtrack Version 1.2 User's Manual",

[8] A. Terebilo, "Accelerator Toolbox for MATLAB",

[9] M. Cornacchia et al. "Running FERMI with one-stage compressor: advantages, layout, performance", 2008

[10] K.Bane et al. "Measurement of compression and emittance growth after the first LCLS bunch compressor chicane", Pac '07