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FULL CHARACTERIZATION OF THE BUNCH-COMPRESSOR DIPOLES FOR FLUTE*

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Abstract

FLUTE (Ferninfrarot Linac- Und Test-Experiment) is a KIT-operated linac-based test facility for accelerator research and development as well as a compact, ultra-broadband and short-pulse terahertz (THz) source. As a key component of FLUTE, the bunch compressor (chicane) consisting of four specially designed dipoles will be used to compress the 40-50 MeV electron bunches after the linac down to single fs bunch length. The maximum vertical magnetic field of the dipoles reaches 0.22 T, with an effective length of 200 mm. The good-field region is ±40 mm and ±10.5 mm in the horizontal and vertical direction, respectively. The latest measurement results of the dipoles in terms of field homogeneity, excitation and field reproducibility within the good-field regions will be reported, which meet the predefined specifications. The measured 3D magnetic field distributions have been used to perform beam dynamics simulations of the bunch compressor. Effects of the real field properties on the beam dynamics, which are different from that of the ASTRA built-in dipole field, will be discussed.

INTRODUCTION

As a linac-based test facility for accelerator research and development as well as a compact, ultra-broadband and short-pulse THz photon source, FLUTE (Ferninfrarot Linac- Und Test-Experiment) is being commissioned and operated at KIT [1-3]. This compact versatile linear accelerator provides an infrastructure for advanced ps and fs electron and photon beam studies and diagnostics. Moreover, it could serve as an injector for laser wakefield accelerators and also the compact storage ring cSTART [4] being designed at KIT. The main design parameters of the electron beam and THz radiation are listed in Table 1.

Table 1: Main Design Parameters of FLUTE

Parameters	Values
Electron energy	40-50 MeV
Electron bunch charge	1 pC to 3 nC
Electron bunch length	1-300 fs
Spectral band coverage	0.1-100 THz
THz E-field strength	up to 1 GV/m
Repetition rate	1-10 Hz

The core accelerator consists of a 7 MeV photocathode RF gun including a focusing solenoid, a 2998 MHz travelling wave linac with a length of 5.2 m, an electron bunch compressor, beam transport magnets and beam diagnostics instrumentations. Consisting of four dipole magnets, the D-shape chicane is the crucial component to produce ultra-short electron bunches [5], a PIC model of which was built using CST [6], as shown in Fig. 1, where the electron bunches having longitudinal correlated energy spread travel from the left to the right. The four dipoles have the same magnetic field strength, while the direction of the field in the first and fourth dipole is opposite to that in the second and third one. The distances between the first two and the last two dipoles are equal. The length of the chicane is about 3 m.

This paper reports the requirements and specifications of the chicane dipoles, the magnetic field measurement and result analysis, and effects of the measured 3D field distribution on the beam dynamics of the bunch compressor.

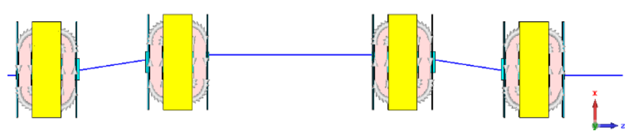

Figure 1: CST PIC model of the FLUTE chicane.

CHICANE DIPOLES AND FIELD MEASUREMENT

Requirements and Specifications

To have sufficient flexibility for the beam dynamics optimization and beam commissioning, the dipoles have been specially designed to cover a wide range of beam dynamics parameters such as beam energy and deflection angle. Both of the C-type and H-type dipole magnets were considered in the early stage [7], whereas the H-type dipoles were finally selected taking advantages of their better field homogeneity in the transverse good-field region. Furthermore, the two dipoles in the middle of the chicane will be installed movable in the beamline to fit with various deflection angles ranging from 0° to 15°.

The concept design of the dipoles was proposed by KIT, while the parameter finalization, magnet manufacturing and the first field measurement were performed at Danfysik. The dipole magnet design is based on a solid steel yoke with air cooled coils. The magnetic field is defined by rose shim on the pole sides, a Purcell-filter on the pole root and an optimized pole end chamfer profile. The magnets are equipped with mirror plates to constrain the magnetic field and reduce the fringe field. Both OPERA [8] and CST have been used to design and simulate the dipole magnet. The CST simulation model is shown in Fig. 2. The main parameters of the chicane dipoles are listed in Table 2.

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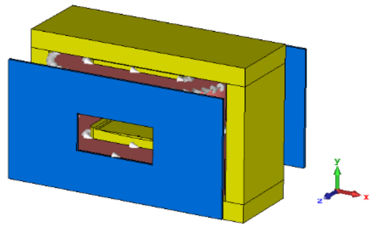

Figure 2: CST model of the FLUTE chicane dipole.

Table 2: Main Parameters of FLUTE Chicane Dipoles

Parameters	Values
Vertical field in centre B_0	0.22 T at 57.3 A
Effective magnet length L_{eff}	200 mm
Good-field region (horizontal)	±40 mm
Good-field region (vertical)	±10.5 mm
$\left\lvert \frac{\Delta B(x,y)}{B_0} \right\rvert_{z=0}$	$<2.4\times10^{-4}$
$\left\lvert \frac{L_{\mathrm{eff}}(x)-L_{\mathrm{eff}}(x=0)}{L_{\mathrm{eff}}(x=0)} \right\rvert_{y=0}$	$<5\times10^{-4}$
Field reproducibility in cycles	$\pm5\times10^{-4}$
Distance between poles	45 mm
Pole and Yoke material	XC 06 steel
Mirror plates material	Armco
Magnet dimensions in x, y, z	440, 310, 320 mm
Magnet weight	225 kg

Field Measurements

The four dipole magnets have recently been measured at KIT. Figure 3 shows the setup of the measurement system. It mainly includes a vibration damped, nonmagnetic optical table, a group of servo motor-driven translation stages, a coordinate calibration system FARO Arm, a 3D Hall probe connected to Senis 3MH5 Digital Teslameter, a 57.3 A power supply, a standard permanent dipole to assist the coordinate calibration and a Zero-Gauss chamber for Hall probe offset zeroing with an accuracy of 0.04 mT. The motors control the 3D position and angle around the z-axis of the Hall probe, which are operated with an XPS-8 Newport controller and EPICS based control system [9].

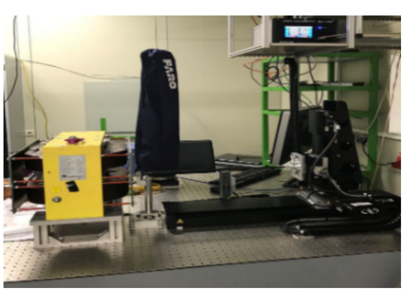

Figure 3: Magnet measurement system at KIT.

The 3D Hall probe measures the magnetic field components in x, y and z directions simultaneously. The 3D distributions of each field component have been measured at different driving currents between 0 and 57.3 A, with a step size of 1 mm and 2 mm. The normalized vertical field component along the magnet axis is plotted in Fig. 4.

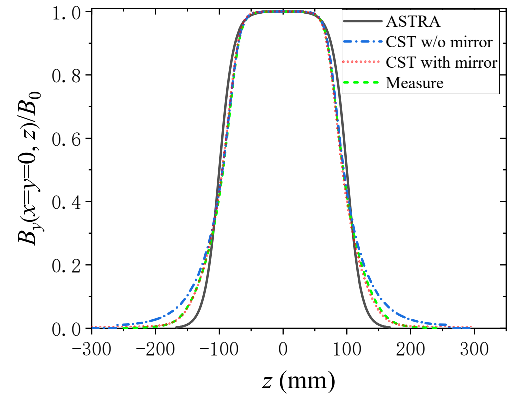

Figure 4: Normalized vertical field component along axis.

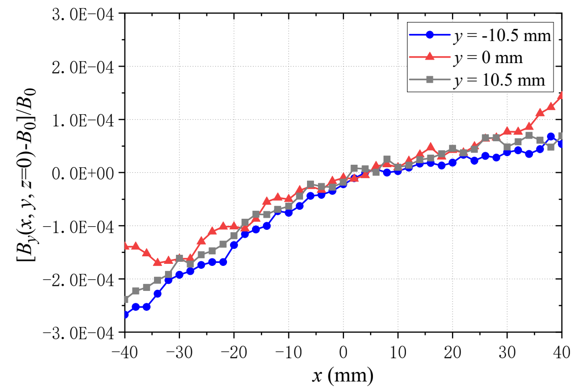

Figure 5: Measured vertical field homogeneity in the transverse good-field region at $z = 0$ for the first dipole at 57.3 A.

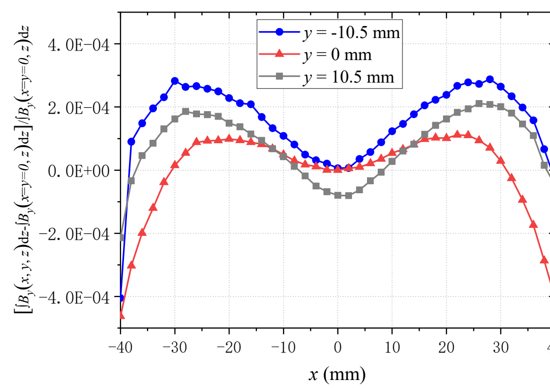

Figure 6: Measured homogeneity of the effective magnet length in the transverse good-field region for the first dipole at 57.3 A.

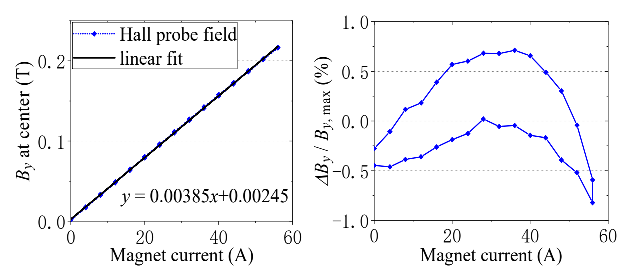

Figure 7: Magnet excitation and linear fit (left), and field deviation from linearity (right) of the first dipole.

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Figure 5 shows the homogeneity of the measured vertical field in the transverse good-field region at $z = 0$ for the first dipole at 57.3 A, which meets the requirement of $<2.4\times10^{-4}$ as listed in Table 2 and also agrees well with the measurement result of Danfysik. In Fig. 6, the measured homogeneity of the effective magnet length in the transverse good-field region for the first dipole at 57.3 A is plotted, which is well below 5×10^{-4} as required. Figure 7 plots the magnet excitation and a linear fit, as well as the field deviation from linearity of the first dipole, which is within ±1% showing a weak Hysteresis effect.

As for the field reproducibility, i.e., the maximum relative deviation of the centre vertical field $B_0=B_y(x=y=z=0)$ from the average value in repeated cycles, it fulfils the predefined specification (within $\pm5\times10^{-4}$) during current ramping down, but is slightly higher during ramping up.

Detailed analysis has been carried out for all the measured fields of the four dipoles. These measurement results reach the design specifications and show good consistence. Among the four dipoles, a difference of 0.5% in the centre vertical field at the same magnet current has been observed, which might be due to the individual magnet property and the errors of the power supply. This observation suggests that it is important to use four power supplies to control the dipoles individually, for the purpose of providing exactly the same magnetic field during beam operation.

EFFECTS OF THE MEASURED 3D FIELD ON THE BEAM DYNAMICS

ASTRA [10] has been used to optimize the beam dynamics design of FLUTE, including the bunch compression in the chicane when the coherent synchrotron radiation (CSR) effect is not significant at very low charge. In the case of 1 pC bunch charge, an RMS bunch length after the chicane has been optimized down to 1 µm (3.3 fs) from 50 µm at the entrance.

When defining a dipole magnet in ASTRA, fringe field decays outside of the magnet as $B_y(d)=B_0[1+\exp(4d/\mathrm{D\_Gap})]^{-1}$, where d is the normal distance to the edge, D_Gap is a taper parameter for the dipole fringe field. The other field components are calculated according to Maxwell's law. Many efforts were put to make the FLUTE chicane dipoles have the same field distribution as ASTRA built-in dipole, including the geometrical optimization and the use of a pair of mirror plates at the magnet ends to constrain the field and reduce the fringe field. However, as shown in Fig. 4, the difference between the measured vertical field B_y and the ASTRA built-in field is still noticeable. There are certain differences in the B_x and B_z components as well. B_x is a weak component that has a slight effect on the vertical phase space, B_z has a focusing or defocusing effect on the vertical phase space, while B_y is the dominant component to deflect the beam horizontally and realize the longitudinal bunch compression.

The measured 3D magnetic field maps have been used to perform beam dynamics simulations of the bunch compressor using ASTRA by defining the namelist CAVITY. A comparison is made for the case of 1 pC in Fig. 8. It can be seen that there is more distortion in the longitudinal phase space when using the measured field maps due to the fringe field. Although the RMS bunch length increases only a few percent compared to the value obtained using ASTRA built-in dipoles, the FWHM (full width at half magnitude) bunch length becomes much larger. This finding suggests that it is important to install an adjustable slit [11, 12] in the middle of the chicane to allow only the central slice of the electron bunch pass through in order to obtain ultra-short bunches.

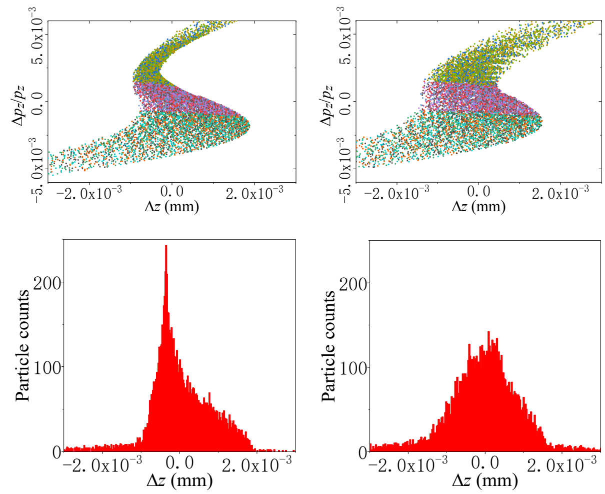

Figure 8: Longitudinal phase space of the compressed bunch at 1 m after the chicane, in the case of 1 pC bunch charge, simulated with ASTRA built-in dipoles (left) and measured 3D dipole field maps (right).

SUMMARY

The RF gun is in operation at FLUTE, the next stages of which include the installation and commissioning of the linac and the bunch compressor. The four specially designed dipoles for the chicane have been measured and analysed recently, in terms of the field homogeneity, excitation and field reproducibility within the good-field regions, which fulfil the predefined requirements. Due to slightly different excitation behaviours of the four dipoles, it is necessary to apply four power supplies to power the magnets individually. It is also important to properly define the cycling during operation, since there is a weak Hysteresis effect when ramping up and down. Because of the imperfection of the dipole fields and the installation errors in the future beamline, a slit collimator with a tunable gap should be applied in the middle of the chicane, and a pair of steering magnets should be installed after the chicane to correct the transverse beam position.

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