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Construction and performance of the magnetic bunch compressor for the THz facility at Chiang Mai University

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ABSTRACT

The Plasma and Beam Physics Research Facility at Chiang Mai University has established a THz facility to focus on the study of ultra-short electron pulses. Short electron bunches can be generated from a system that consists of a radio-frequency (RF) gun with a thermionic cathode, an alpha magnet as a magnetic bunch compressor, and a linear accelerator as a post-acceleration section. The alpha magnet is a conventional and simple instrument for low-energy electron bunch compression. With the alpha magnet constructed in-house, several hundred femtosecond electron bunches for THz radiation production can be generated from the thermionic RF gun. The construction and performance of the alpha magnet, as well as some experimental results, are presented in this paper.

1. Introduction

Femtosecond electron and photon pulses have become interesting tools for basic and applied applications [1–3]. Short electron pulses can be used directly [1] or to generate intense THz radiation [4], ultra-short X-ray pulses [5], and free-electron lasers [6].

Short electron pulses can be produced in a straightforward way by using linear accelerators and bunch compressors. In the case of using a chicane bunch compressor [7], a long relativistic electron bunch with a small energy spread is accelerated in a linear accelerator section at zero-phase, such that the head of the bunch loses energy and the particles in the tail gain energy, while the energy of the particles in the center do not change. In chicane magnets, the high-energy particles in the bunch tail travel a shorter path than the low-energy particles in the bunch head, thereby leading to bunch compression. After sufficient further acceleration, the energy spread becomes small again, and a new step of bunch compression can be implemented.

In the case of using alpha-magnet bunch compression, sub-picosecond electron bunches can be produced in a smaller facility from a thermionic-cathode radio-frequency (RF) gun and the alpha magnet. It has been possible to produce electron pulses as short as 120 fs rms and a bunch intensity of 100 pCb by using such a compression system at the Stanford SUNSHINE facility [4,7,8]. A similar system to generate femtosecond electron bunches has been constructed and installed at Chiang Mai University. The main components of the system are an S-band 1½-cell RF gun with a thermionic cathode [9], an alpha magnet, and a SLAC-type linear accelerator (linac), as shown in Fig. 1(a). At the exit of the RF gun, electrons have been accelerated to about 2.0–2.5 MeV with a well-defined correlation between energy and time [Fig. 1(b)]. The electron bunch of 20–30 ps from the RF gun enters the alpha magnet at an angle of 42.29 degrees with respect to the magnet axis. The particles follow a close loop similar to the letter α and exit the magnet exactly at the entrance point. In the alpha magnet, higher energy electrons follow longer paths, while lower energy electrons follow shorter ones. Therefore, the lower energy electrons have a chance to catch up to the higher energy electrons in the front, thereby leading to bunch compression. The electron bunches are then accelerated in a 3-m single-section linear accelerator and guided to the experimental station. With an over-compression at the alpha magnet [Fig. 2(a)], the bunches are compressed to less than 1 ps at the experimental station [Fig. 2(c)]. Due to velocity dispersion, if the bunches are well compressed at the magnet exit [Fig. 2(b)], then they would not be optimum at the experimental station [Fig. 2(d)].

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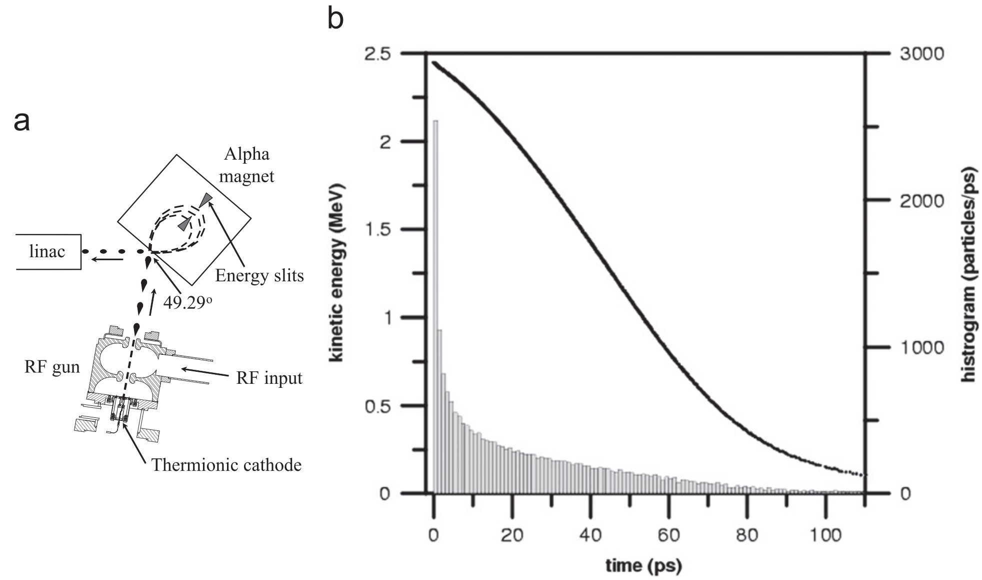


Fig. 1. (a) Schematic diagram of the bunch generation and compression system, and (b) particle distribution in energy-time phase space with a histogram at the RF-gun exit.

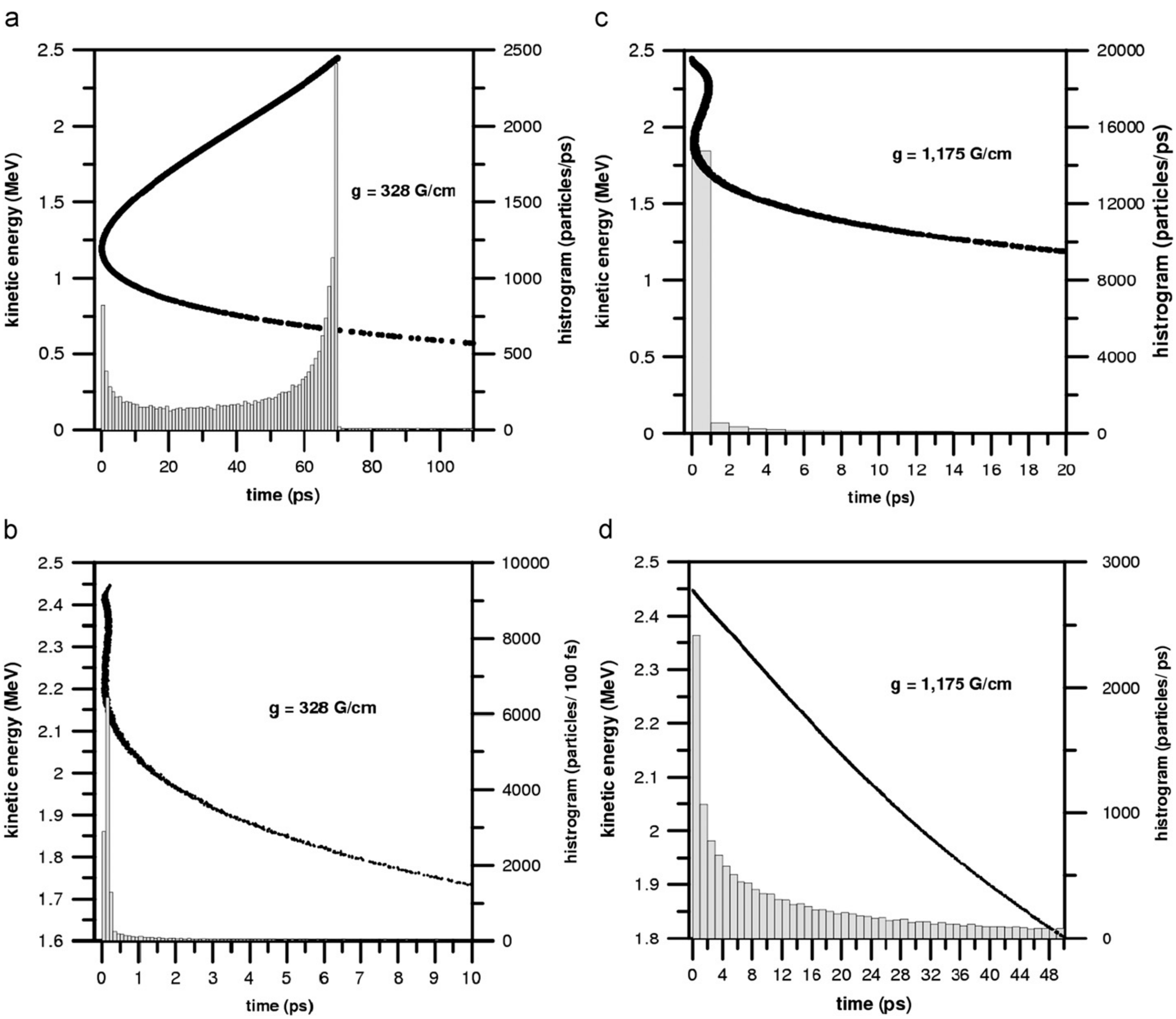


Fig. 2. Particle distribution in energy-time phase space with a histogram: (a) and (c) are at the RF-gun exit, and (b) and (d) are at the experimental station.

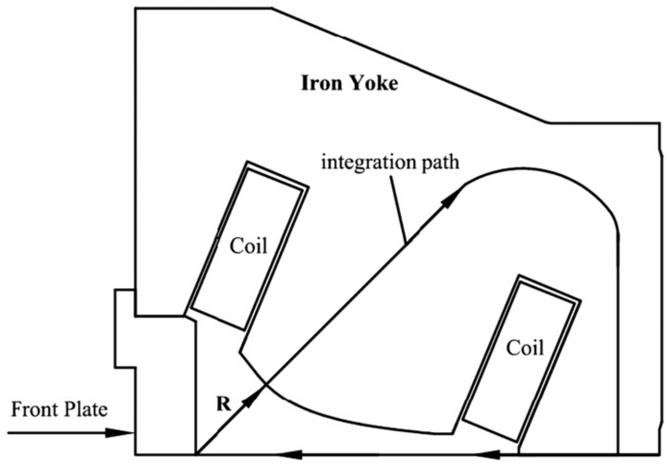


Fig. 3. Integration path in the alpha magnet.

Table 1
Alpha-magnet design parameters.

Parameters	
Maximum field gradient	450 G/cm
Pole radius	10 cm
Good-field region (extent in X)	20 cm
Maximum gradient error	±0.1%

Bunch compression computer code [10] was employed to study the bunch compression of our system by using some information from the RF-gun study detailed in Rimjaem et al. [9]. Through a series of calculations, the optimum field gradient to generate the short bunch was then obtained. For our system, the maximum alpha-magnet field gradient of 450 G/cm is expected for producing a short electron bunch at 20 MeV [9].

2. Design of the magnetic bunch compressor for the THz facility at Chiang Mai University

The alpha magnet and its properties were first described by Enge [11]. It has the shape of half an asymmetric quadrupole magnet, with two poles and a mirror plate (front plate) terminating the field across the vertical midplane. It is called asymmetric because the pole face extends further horizontally than vertically, in order to provide a large horizontal and uniform field gradient region. The sequence of this alpha-magnet design follows the quadrupole design, which is discussed in more detail in Wiedemann [12] and Fischerm [13]. This magnet design was modified and redesigned based on the alpha magnet of the Stanford Synchrotron Radiation Lightsource Project [14].

A straightforward way to estimate the excitation currents of the magnet is to use the integral form of Ampere's Law:

$$\oint \vec{H} \cdot \vec{dl} = NI \tag{1}$$

By using the approximation that the permeability of iron is infinite and by choosing the integration part as shown in Fig. 3,

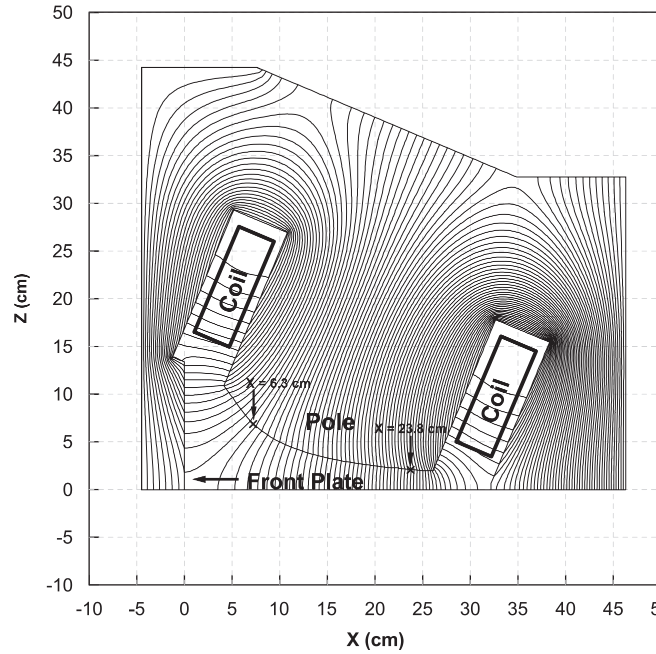


Fig. 4. Alpha-magnet pole profile for POISSION input and the magnetic field line of the alpha magnet.

the integration starts from the magnet axis. The result is:

$$NI = \int_0^a \frac{ar}{\mu_0} dr = \frac{ga^2}{2\mu_0} \tag{2}$$

where g is the field gradient (Tesla/m), a is the pole radius (m), N is the number of turns, and I is the current (Ampere). With the design parameters shown in Table 1, NI=17,905 Ampere-turn. By considering the space available for the magnet coils and the size of the hollow copper wires, the number of turns, N=70 turns, was selected. The magnet would require a maximum excitation current of 255 Ampere to provide the field gradient of 450 G/cm.

2.1. Computer simulation

The pure quadrupole field, which gives a constant field gradient along the vertical and horizontal midplane, can be created from infinitely wide hyperbolic poles. In practice, the magnet poles are cut to place the excitation coils, thus causing the field gradient to drop near the corner of the poles. In the case of the alpha magnet, there are concerns about the homogeneity of the field gradient and especially the gradient drop near the pole corner and the front plate. The field gradient drop can be compensated by iron shimming near the upper end of the hyperbola pole by using a tangential technique [12]. At proper positions on the hyperbola pole profile, the tangential lines are extended to intercept with the pole root for iron shimming. The pole profile is optimized by using by POISSION [15], which calculates the magnetic fields from the input pole profile (Fig. 4) as well as the field gradients. The calculation results indicated that the position x=6.3 cm and x=23.8 cm are the best starting points for tangential shimming, which gives a gradient error of less than ±0.1% along the midplane, as shown in Fig. 5.

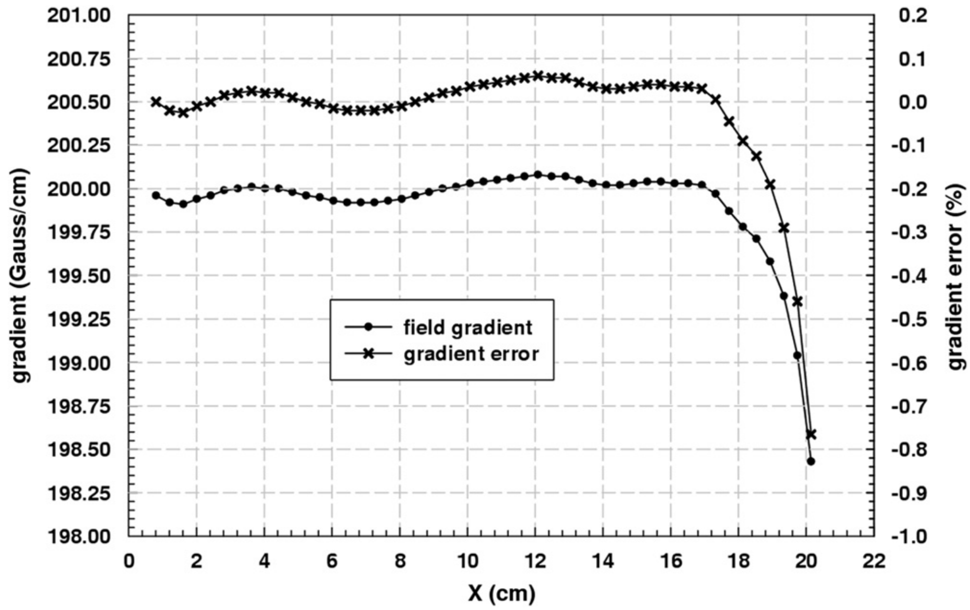


Fig. 5. Magnetic field distribution at midplane from the hyperbola pole compared with the final design.

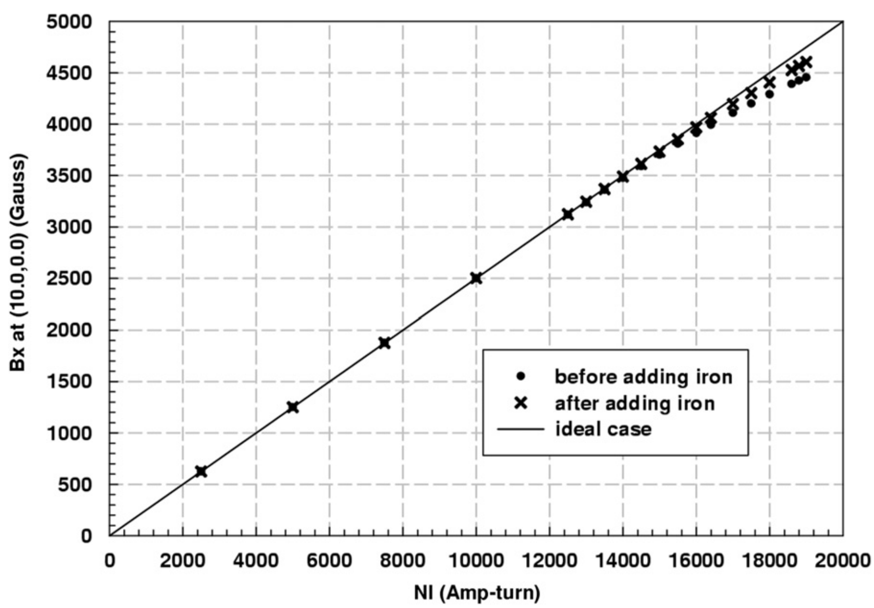


Fig. 6. Magnetic field at $x=10$ cm as a function of current (NI).

2.2. *Magnetic field saturation*

Magnetic field saturation [11] occurs at high excitation currents, which causes some regions in the magnet core to have too high of a magnet flux density. Fig. 4 shows that the return yoke and the front plate are the regions that have a high flux density. To reduce this high flux density, the thickness of the front plate and the return yoke are increased. Fig. 6 shows the magnetic field from POISSON before and after adding iron at these two regions. The calculations show that after adding more iron, the saturation occurs at higher currents (from $>14{,}000$ Ampere-turn to $>17{,}000$ Ampere-turn).

3. Construction of the alpha magnet

3.1. *Construction of the magnet core*

The magnet core is constructed from low-carbon steel (0.035% carbon, $\mu_r \sim 2500$–3000). The core is composed of two magnet poles and a front plate. Each pole piece was fabricated from nine iron laminations. All components of the magnet core were machined by a computer numerical controlled (CNC) machine. Fig. 7(a) shows a pole piece lamination of the alpha magnet. Nine laminations are stacked and tightened together by long bolts and nuts, as shown in Fig. 7(b). The complete assembly of the magnet core is shown in Fig. 7(c).

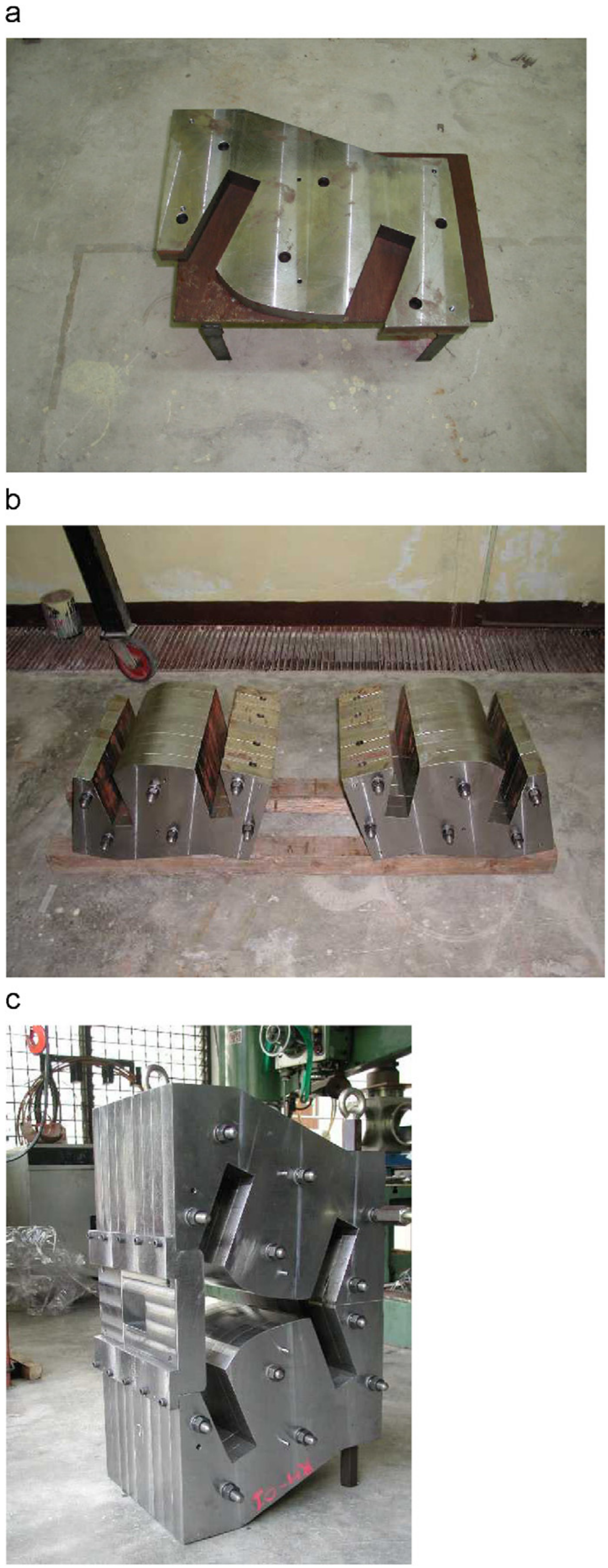


Fig. 7. (a) A pole piece lamination of the alpha magnet, (b) alpha-magnet poles, and (c) alpha-magnet assembly.

3.2. Construction of the magnet coils

The magnet coils are constructed from $1 \times 1\,\mathrm{cm}^2$ copper wire, with a 4-mm-diameter cooling hole. The double pancake technique is used to wind the hollow copper wire. The wire is wound by using a winding platform mounted on a rotating table. In this design, one double pancake has two layers of copper wire, and each layer has five turns. Before winding the coil, the wire is wrapped by glass cloth tape as insulation. The wire is wound five turns for the first layer, and it is cut and connected to the other end for the winding of the second layer. The wire is then wound five turns in the opposite direction of the first layer. The water connectors are connected to both ends of one double pancake. Seven double pancakes are connected and stacked together to be one alpha-magnet coil, as shown in Fig. 8(a). The resistance of the two coils is 94 mΩ, resulting in the total power dissipation of 7.9 kW at a current of 290 A. The 10 °C water, with flow rate of 10 l/s, is used to remove most of the heat dissipation. The complete assembly of the alpha magnet is shown in Fig. 8(b).

4. Performance of the magnetic bunch compressor

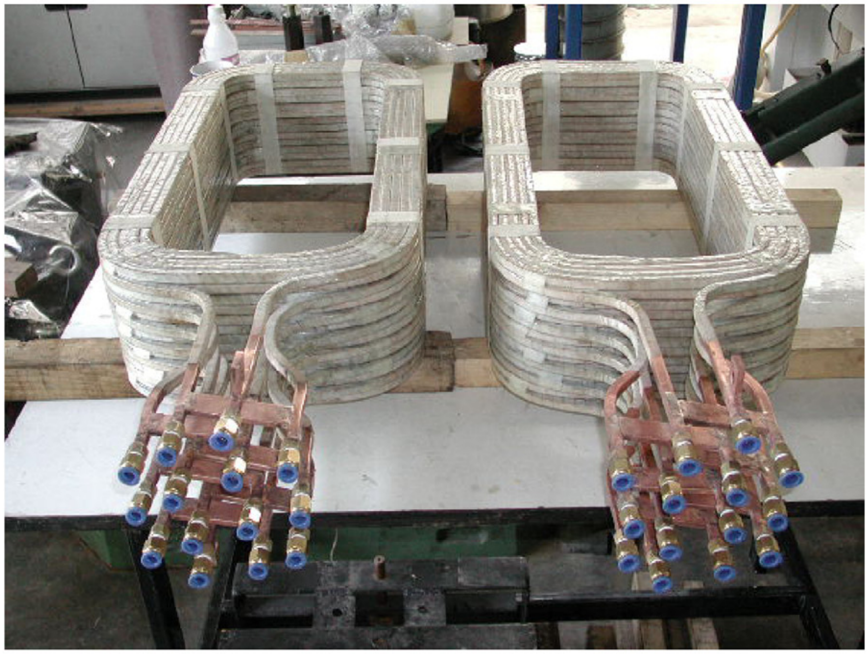
4.1. Magnetic field measurement

The alpha-magnet field distribution is measured along the X direction at the midplane by using a DMT-130-PS Hall effect Teslameter. The magnetic field gradient is then derived from the field measurement. Fig. 9 shows the excitation curve of the alpha magnet from calculations and measurements. A maximum gradient of 465 G/cm can be achieved, limited by the DC power supply. Saturation was observed at a current higher than 150 A. With sufficient water cooling, there is no significant temperature rise during operation.

4.2. Bunch length measurement

At the experimental station located downstream of the linac, the 8- to 10-MeV electron bunches were used to generate coherent transition radiation for electron bunch length measurement. By placing a 25-μm-thick aluminum foil (Al foil) at 45 degrees with respect to the electron path, the backward transition radiation is emitted perpendicular to the beam axis. A far-infrared Michelson interferometer was employed to measure the electron bunch length by an autocorrelation technique [16]. The coherent transition radiation is collimated by a gold-coated parabolic mirror. The radiation beam exits through a high-density polyethylene window and enters a Michelson interferometer. The interferometer consists of a beam splitter, a fixed mirror, and a movable mirror. In the Michelson interferometer, the radiation is split into two parts by a beam splitter, and it then travels in different directions to be reflected back by the mirrors. After reflection, the two radiation pulses are combined again and detected by a pyroelectric detector for intensity determination. By scanning the movable mirror, the radiation intensity as a function of the optical path difference, called the interferogram, was obtained, as shown in Fig. 10. For a Gaussian bunch distribution, the full width at half maximum (FWHM) of the interferogram is $4\sqrt{\ln 2}\sigma_Z$. The bunch length measurements for various alpha-magnet gradients have been conducted, and the results are shown in Fig. 11.

The measurement results show that short electron bunches can be generated when the alpha-magnet gradient is higher than 300 G/cm. However, the calculation predicted the shortest bunch a



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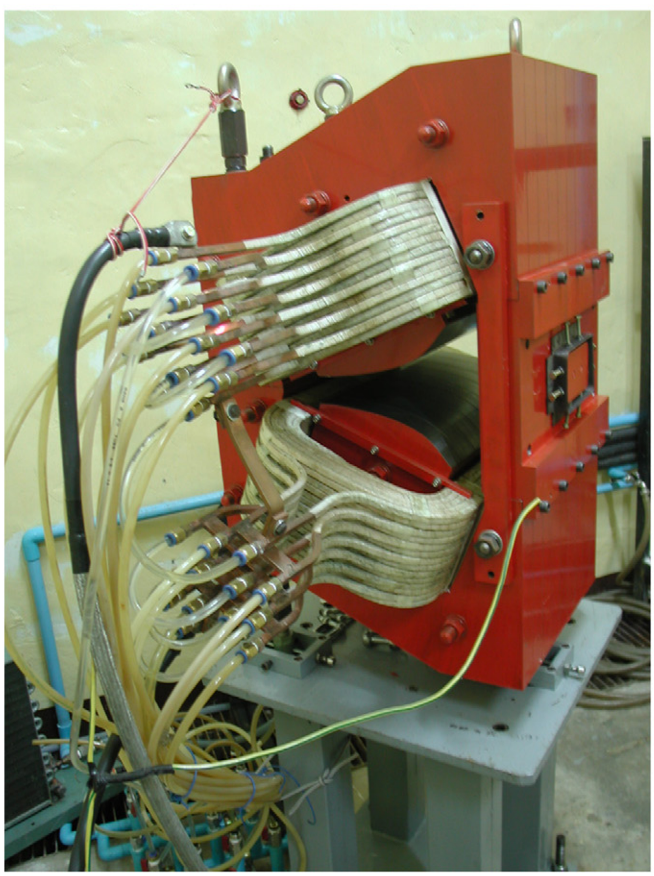

Fig. 8. (a) Two complete coils, and (b) a completed alpha magnet.

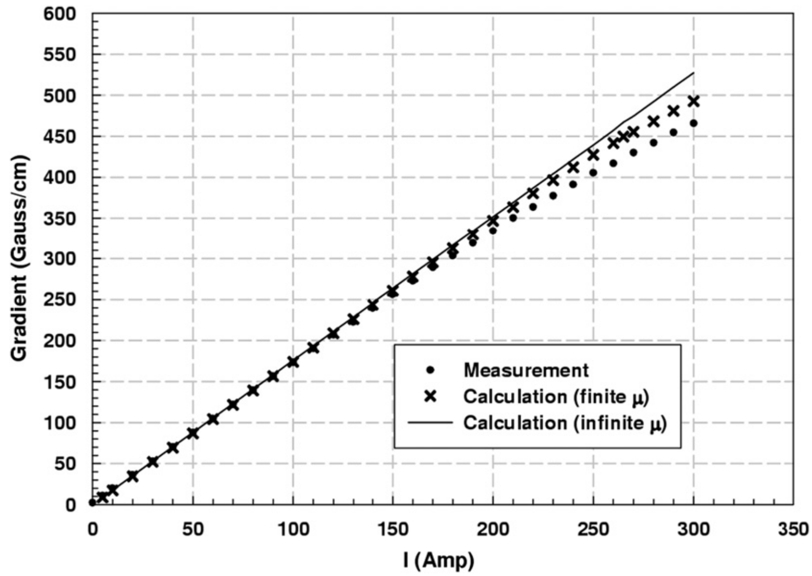

Fig. 9. Excitation curve of the alpha magnet from calculation (infinite μ and finite μ) and measurement.

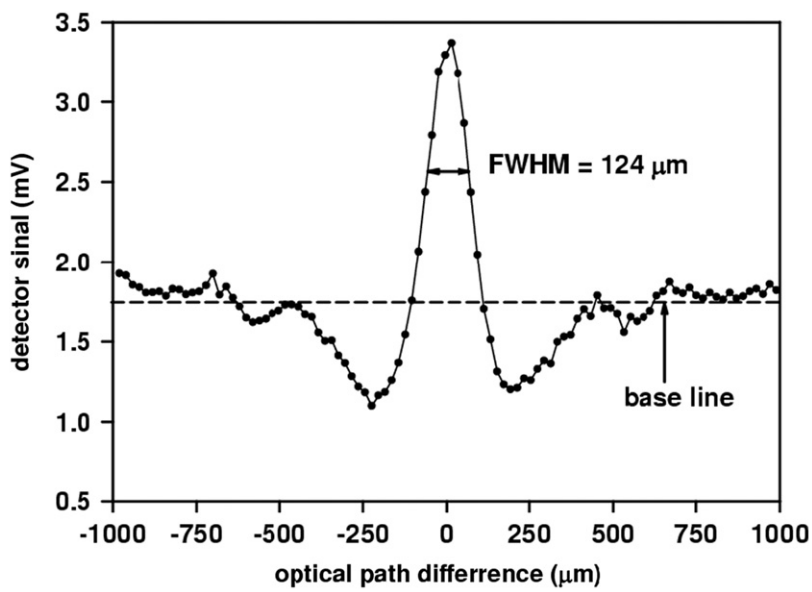

Fig. 10. An interferogram obtained from the bunch length measurement.

when using the alpha-magnet gradient of 328 G/cm for the 10-MeV electron beam (see Table 2). Equally short bunches can be obtained from our system through a broad range of alpha-magnet gradients due to the large energy spread (8–12 MeV). Calculations from the bunch compression program show that different electron beam energies require different alpha-magnet gradients to generate the minimum bunch length, as shown in Table 2. If the electron bunches have a large energy spread, then some electrons are compressed at a specific alpha-magnet gradient, while others are under-compressed or over-compressed, depending on their energy. It is therefore possible that equally short electron bunches of a large energy spread beam can be obtained through a broad range of alpha-magnet gradients.

5. Conclusion

An alpha magnet was successfully designed, constructed, and tested at the Plasma and Beam Physics Research Facility at Chiang Mai University. With this alpha magnet constructed in-house, a few hundred femtosecond electron bunches for THz radiation production can be generated from the thermionic-cathode RF gun. The experimental results show that electron bunches as short as $\sigma_z \sim 200$ fs can be generated from the system. Electron bunch length may be reduced with energy spread and lattice optimization. Our short electron bunches will be used to produce THz radiation for spectroscopy experiments and THz imaging applications.

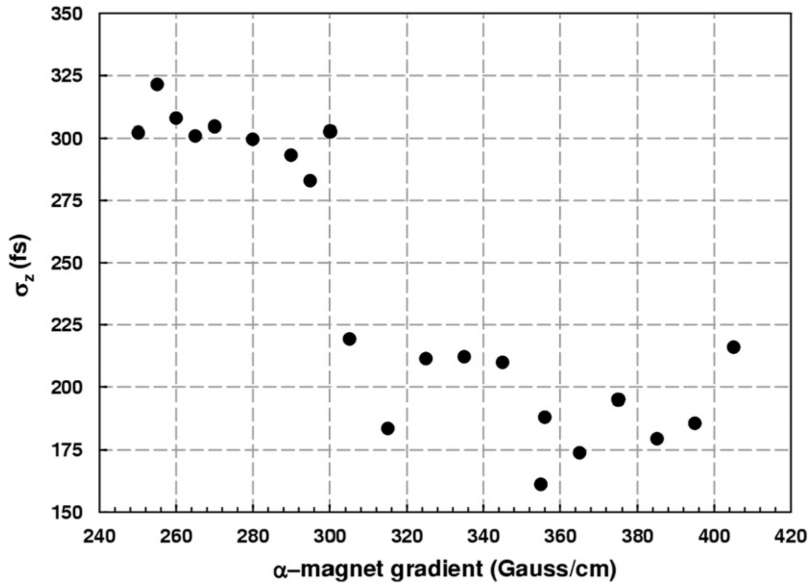

Fig. 11. Bunch length as a function of the alpha-magnet gradient.

Table 2
Alpha-magnet gradient for a minimum electron bunch of different electron energies.

Electron energy (MeV)	Alpha-magnet gradient (G/cm) (for minimum electron bunch)
8.0	298
9.0	315
10.0	329
11.0	342
12.0	352

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