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Design and testing of focusing magnets for a compact electron linac ☆

Qushan Chen [a], Bin Qin [a,*], Kaifeng Liu [a], Xu Liu [a], Qiang Fu [a], Ping Tan [a], Tongning Hu [a], Yuanji Pei [b]

[a] State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China
[b] National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230029, China

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ABSTRACT

Solenoid field errors have great influence on electron beam qualities. In this paper, design and testing of high precision solenoids for a compact electron linac is presented. We proposed an efficient and practical method to solve the peak field of the solenoid for relativistic electron beams based on the reduced envelope equation. Beam dynamics involving space charge force were performed to predict the focusing effects. Detailed optimization methods were introduced to achieve an ultra-compact configuration as well as high accuracy, with the help of the POISSON and OPERA packages. Efforts were attempted to restrain system errors in the off-line testing, which showed the short lens and the main solenoid produced a peak field of 0.13 T and 0.21 T respectively. Data analysis involving central and off axes was carried out and demonstrated that the testing results fitted well with the design.

1. Introduction

Focusing magnets are widely used in modern radio-frequency (RF) linear accelerators, for the purpose of emittance compensation, transverse focusing and electron cooling, etc. [1–3]. At the same time, solenoid field errors have great influence on electron beam qualities. It has been reported that residual emittance and longitudinal beam temperature are very sensitive to the solenoid strength in some applications [4,5]. So, a reliable and efficient method of designing focusing solenoids is desired.

Based on the compact terahertz free electron laser (THz-FEL) oscillator project proposed by Huazhong University of Science and Technology (HUST), a magnetic focusing system composed of a short lens and a main solenoid is designed to transport intense electron beams with low emittance ($<15\pi$ mm · mrad) and low energy spread ($<0.3\%$) to the downstream undulator delivered by the transfer line [6–8]. Fig. 1 shows the layout of some key components including the transfer line, which are mainly configured for the consideration of beam quality requirements and mechanical support. In general, the focusing magnets will affect the transverse motion and work as pre-matching to the transfer line. Overall effects of the focusing magnets will be revealed via beam dynamics simulation.

Apart from the focusing performance, compactness is also an important factor in lots of modern accelerator applications, especially in our case. The same view comes from the fact that superconducting solenoids are applied at an increasing rate in accelerators [9,10]. For a range of technical and economic considerations, superconducting solenoids are not adopted in our project. But it is still possible to achieve a relatively compact structure through a series of optimization methods, including employing coaxial absorber load and using soft iron instead of bucking coils to reduce fringe fields. Another highlight of our design is that the current configuration of the main solenoid is adjustable to satisfy all different energy requirements varying from 6 to 14 MeV.

2. Physical design

2.1. Analysis of beam envelope equation

Focusing characteristics of solenoids have been readily analyzed in previous works [11,12]. In practice, these equations are difficult to solve and there should have a lot of trial and errors before the focusing strength is set. For the specific case in HUST's THz-FEL, we have analyzed the envelope equation and taken some approximation to find a simple method to set the peak strength.

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* Corresponding author. Tel.: +86 27 87557634.
E-mail address: bin.qin@mail.hust.edu.cn (B. Qin).

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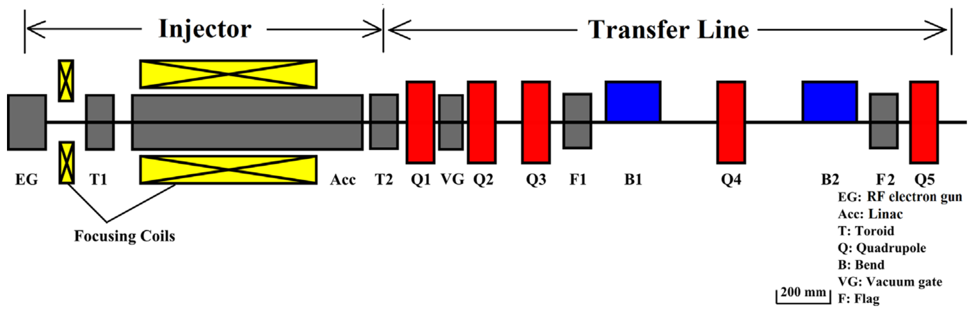

Fig. 1. Layout of the compact THz-FEL injector and the transfer line. Note only the longitudinal dimensions are proportional to real arrangement.

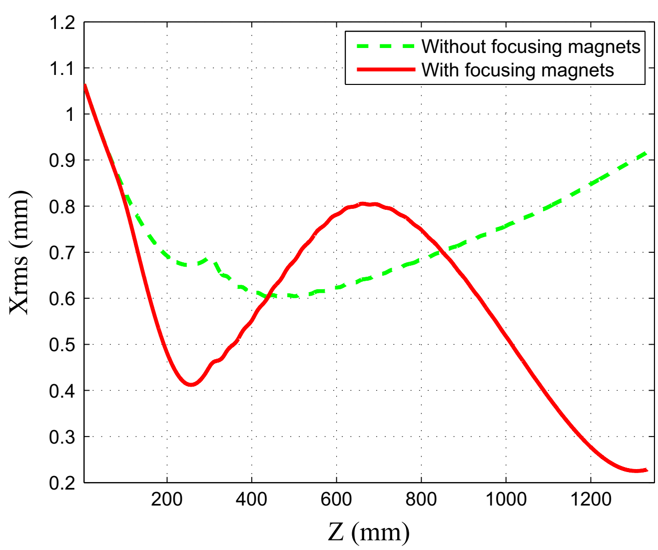

Fig. 2. Electron beam radius evolution along the accelerating structure with and without the focusing magnets. The beam energy is 14 MeV in this case.

Generally, the evolution of the beam envelope in the paraxial limit is [12]

$$R'' + \frac{(\beta\gamma)'}{\beta\gamma}R' + \frac{N(z)}{\beta\gamma}R - \frac{\epsilon^2}{(\beta\gamma)^2}R^{-3} = 0 \tag{1}$$

$$N(z) = \frac{e^2 B_z^{*}2}{4\beta\gamma} - \frac{e\mu_0 I}{2\pi m_e c R^2 (\beta\gamma)^2} - \frac{\cos\phi}{2\beta}\frac{\partial E_0^*}{\partial z} + \frac{k(1-\beta\beta_\varphi)E_0^*\sin\phi}{2\beta\beta_\varphi} \tag{2}$$

where R is the beam envelope, β and γ are the relativity factors, ϵ is the normalized emittance, e and m_e are the charge and rest mass of an electron, μ_0 is the permeability of vacuum space, c is light speed in vacuum space, ϕ is the acceleration phase with respect to RF wave, k is the wave number, β_φ is the phase velocity normalized to the light speed in vacuum space, I is the average beam current over one RF period, E_0^* is the normalized axial electric field and is defined as $E_0^* = eE_0/m_e c^2$, and B_z^* is the normalized axial magnetic field and is defined as $B_z^* = eB_z/m_e c$.

It is supposed that the following four conditions are satisfied in our case: (1) relativistic beams, (2) constant gradient accelerating structure, (3) electrons are accelerated at the peak phase, and (4) normalized emittance is on the mm rad level or less. Then the beam envelope equation can be reduced to

$$R'' + \left(\frac{B_z^{*}2}{4\gamma^2} - \frac{e\mu_0 I}{2\pi m_e c R^2 \gamma^3}\right)R = 0. \tag{3}$$

We define $\Pi = ((B_z^{*}2/4\gamma^2) - (e\mu_0 I/2\pi m_e c R_s^2 \gamma^3))$ and it is the synthetical effects of the external magnetic force and the space charge force. It is clear that beam envelope oscillates for $\Pi > 0$ and increases steadily for $\Pi < 0$. So only if $\Pi > 0$ we may get focused beams. After comparing the two forces for different focusing strength and beam radii, it was found that external magnetic strength of 0.2 T would be appropriate to radially compress electron bunches to less than 0.2 mm in our case.

2.2. Beam dynamics simulation with the focusing magnets

With the above discussion, optimization of the focusing strength goes to around 0.2 T. To determine the magnetic field quantitatively, beam dynamics simulation was performed with the help of PARMELA [13].

The magnetic field distribution was optimized according to the focusing effects for various beam energies. Beam radius, energy spread, emittance and bunch charge were selected as the assessment criteria. More detailed analysis on the beam dynamics can be found in [14] and this subsection only focuses on the simulation results. For an ideal focusing scheme, electron bunches should be focused to the minimum spot size at the end of the linac or the start of the transport line. After several trial and errors, an optimized field distribution with a peak field of 0.21 T was confirmed and PARMELA showed a quasi-parallel electron beam with an RMS radius of 0.22 mm could be obtained, with other criteria at acceptable level. Fig. 2 shows the electron beam radius evolution with and without the focusing magnets in the 14 MeV case.

3. Technical design

3.1. Challenges and solutions

A series of technical issues need to be settled before the focusing magnets can be put into practice. For the demand of compactness, collinear load coated with magnetic alloy was adopted to absorb remanent power at the end of the linac, which greatly reduced the inner radius of the main solenoid [15,16]. To generate a peak magnetic field of 0.2 T, first proposed scheme was using several segments of solid copper coils separated by metal plate for water cooling, which allowed the maximum current density to be 1 A/mm^2. Preliminary research found that under this scheme the outer diameter of the main solenoid would be more than 600 mm and the total weight would be more than 700 kg. To further reduce the size and weight of the focusing coils, water cooled cable was selected and the current density could reach 10 A/mm^2 according to present state of art.

Another challenge was making the coils to satisfy different energy requirements, which required flexible current configuration. Meanwhile, for the consideration of cooling effect, the main solenoid was divided into 7 segments. The segments were cooled independently while they could be cascaded freely when driven by