FOCUSING MAGNETIC FIELD DESIGN FOR A FEL LINAC

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Abstract

A linac-based Free Electron Laser is planned to be built in Huazhong University of Science and Technology (HUST). As an important component of the linac, the focusing magnetic field is carefully designed. Space-charge force is calculated at first to give a rough estimation of the focusing field. Start-to-end simulation shows that the magnetic field has only significant effect on spot size and phase space. With the final designed field, 3-ps-length (FWHM) pulse containing 200pC electrons can be obtained and the corresponding RMS normalized emittance and RMS radius are 7 πmm·mrad and 0.25 mm, respectively. Finally, a new double-peak scheme is discussed and excitation current is proposed as the evaluation index.

INTRODUCTION

For a linac-based FEL, the performance depends on the quality of electron beams generated by the injector. In a long wavelength FEL oscillator proposed by HUST, the injector consists of an EC-ITC RF gun [1] and a linac, which is operated at 2856MHz and designed to accelerate the beam energy from 2.5 MeV up to 10 ~ 14 MeV. Since the beam energy generated by electron gun is low, it is usually to use a solenoid to focus the beam. In the original design, as shown in Fig. 1, a magnetic lens just following the gun is taken into consideration. And for the sake of compactness, the maximum dimensions of the magnetic lens and solenoid are restricted (see Table 1).

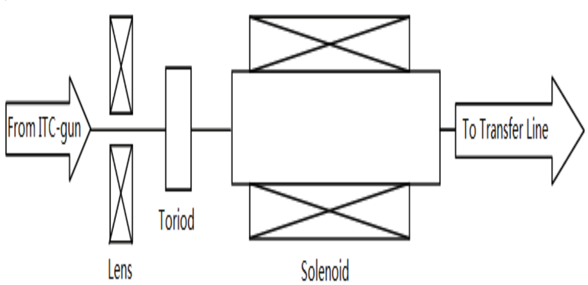

Figure 1: Focusing system for the linac.

Table 1: Maximum Dimensions of Lens and Solenoid

	Outer radius	Length
Lens	200 mm	70 mm
Solenoid	200 mm	770 mm

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As a main part of the focusing system, solenoid is designed to restrain the space-charge effect and compress the spot size. The design process is as the following:

- Calculate the space-charge force to give a rough estimation of the focusing field.
- Optimize the magnetic field distribution to make the electron pulse meet all the desired requirements (see Table 2) at the exit of linac.
- Design practical layout of coils to generate the desired magnetic field distribution.

DESIGN PORCESS

Step 1: Space-charge Effect Estiamtion

The energy of the electron beam generated by the EC-ITC RF gun is about 2.5 MeV, which implies a space-charge-dominated relativistic beam [2]. In fact, the space-charge force will make a difference all through the linac while its actual effect mainly depends on the beam energy and spot size (see the green line in Fig. 3). For parallel input beams, it is supposed that the required magnetic force would be larger in the drift space than that in the acceleration space due to the smaller energy factor (γ) of the former. However, it is usually not that case as the spot size will become much smaller after the focusing process in the drift space. As a result, the space-charge effect in the acceleration space won't vanish dramatically and still relatively high magnetic field is needed. So if an efficient design process is desired, a rigorous comparison between space-charge force and magnetic force must be made. Reference [3] gives detailed derivation on space-charge force. When the cylindrical beam model is adopted, the force produced by the magnetic field and the beam respectively are

$$F_{m\_field} = -\frac{e^2 B_z^2}{4\beta\gamma m_0^2 c^2} r \quad (1)$$

$$F_{beam} = \frac{eI\left(1-\beta^2\right)}{2\pi R_s^2 m_0 \beta^2 c^3 \varepsilon_0} r \quad (2)$$

where I is the average current over one RF period and R_s is the radius of the beam. The two equations above show that the magnetic force is always for focusing while the space-charge force is always for defocusing. Moreover, both F_{m_field} and F_{beam} are proportional to the distance away from the axis, so by comparing the coefficients of the two expressions we can find the relationship between the two forces.

According to the output of the EC-ITC RF gun, the average current over one RF period is 1 A and the

ISBN 978-3-95450-122-9

characteristic radius (RMS radius) is about 1.1 mm. When the beam energy increases from 2.5 MeV to 14 MeV, both coefficients of the two forces can be calculated for specific B_z and R_s, respectively. It is clear from Fig. 2 that a magnetic field with average intensity of 0.1 T is enough to compress the beam radius to below 0.2 mm. It is more or less the case but there is still much work to do before getting the final distribution.

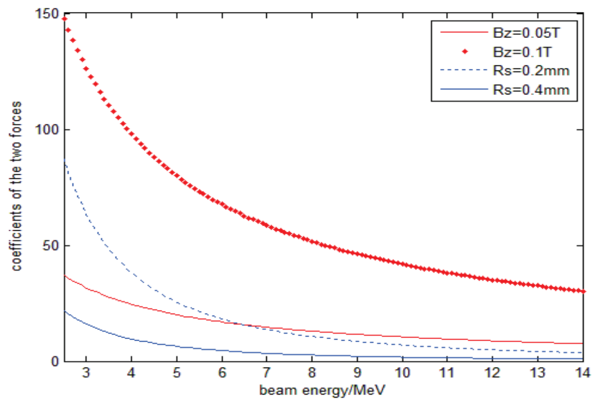

Figure 2: Coefficients of the two forces vary with the beam energy.

Step 2: Magnetic Field Optimization

The space-charge estimation only gives a rough value for the magnetic field and the spot size is always changing both in the drift space and the acceleration space. Then Parmela is used for the beam dynamic simulation, from which the magnetic field distribution is adjusted precisely.

As for parallel input beams, the lens should be put into use (scheme 1) because of the remarkable space-charge force in low energy. However, the phase space (see Fig. 4) of the input beam indicates an obvious focusing trend which implies much less or no extra magnetic force is needed. Otherwise, the spot size will rebound soon after and then larger focusing force of the solenoid is needed to compress the beam spot again. The blue line in Fig. 3 shows the beam envelope when a magnetic lens is used, in which case the peak field strength of the magnetic lens and the solenoid are 0.16 T and 0.22 T, respectively.

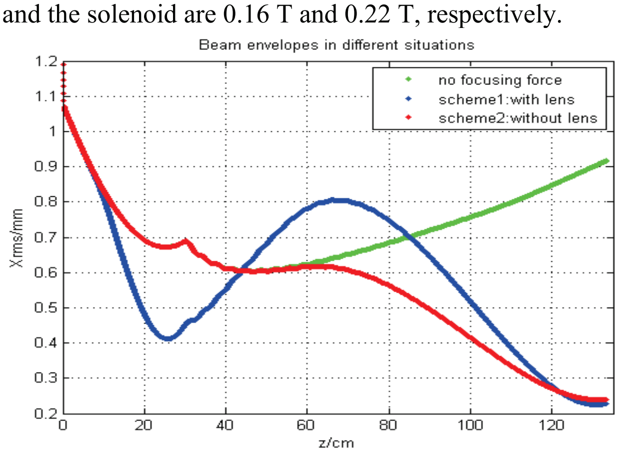

Figure 3: Beam envelopes in three different situations.

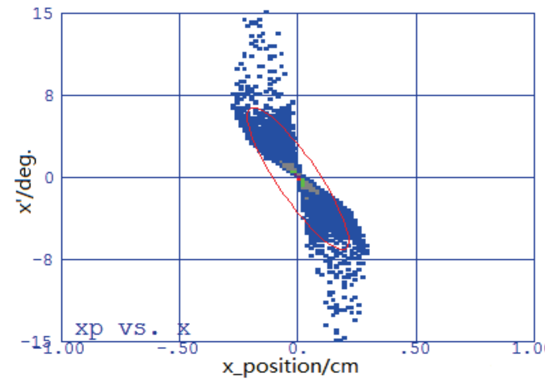

Figure 4: Phase-space plot at the entrance of the linac.

The rebound process can be seen as waster of magnetic field，so we come up with a scheme (scheme 2, see Fig. 3 and Fig. 5) in which the beam radius decreases monotonously. Comparing to the original design, scheme 2 is much easier and cheaper not only because the lens is left out, as well as it reduces the magnetic intensity produced by the solenoid, while the output beam is almost the same as that of scheme 1.

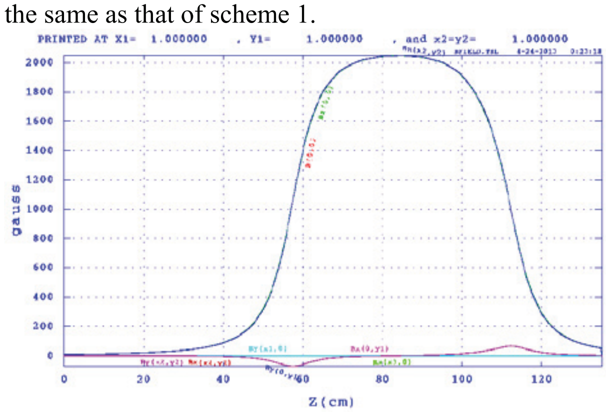

Figure 5: Magnetic field distribution of scheme 2.

Apart from spot size, some other qualities are also checked for both the schemes. It is found that even without any extra focusing force the beam is still able to meet the requirements of emittance and energy spread at the exit of linac if only a proper injection phase of the beam is satisfied. For this very linac, it is best to put the pulse 10 degrees ahead of the summit of RF wave. Fig. 6 and Table 2 show the beam quality at the exit of the linac under scheme 2.

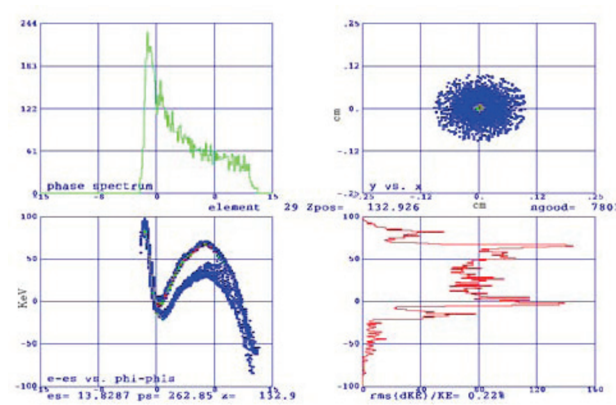

Figure 6: Beam quality at the exit of linac under scheme 2.

Table 2: Beam Quality at the Exit of Linac

	Design targets [4]	**Simulation results**
Beam Energy	8 ~ 14 MeV	14 MeV
Micro-pulse Length (FWHM)	~ 5 ps	3 ps
Effective Charge	200 pC	200 ~ 220 pC
Energy Spread (RMS)	<0.5%	0.22%
Normalized Emittance	<15 πmm·mrad	7 πmm·mrad

A New Idea: Sharp-increased Field

In cylindrical coordinate system, the angular and radial motion of electron is described as

$$\frac{1}{r}\frac{d}{dt}\left(mr^2\dot{\theta}\right)=eE_\theta-e\dot{r}B_z+e\dot{z}B_r \qquad (3)$$

$$\frac{d}{dt}\left(m\dot{r}\right)=mr\dot{\theta}^2+eE_r-e\dot{z}B_\theta+er\dot{\theta}B_z \qquad (4)$$

From equation (3) it is known that the radial magnetic field makes a contribution to angular velocity while the radial component comes from the gradient of longitudinal component.

$$B_r(z,r)\approx-\frac{1}{2}\frac{\partial B_z(z,r)}{\partial z}r \qquad (5)$$

According to reference [5], the ascent part of the longitudinal component makes electrons get angular velocity, which in turn enables the longitudinal component to produce focusing force, and then electrons lose angular momentum during descent part. Based on this point, we can design a new distribution that has larger ascent gradient than descent gradient. As a result, the electrons will get remanent angular momentum after they go through one peak, following which another peak can take advantage of the extra angular momentum. It is better to place the former peak in low energy region as the angular velocity is inversely proportional to particle energy. So we come up with a new scheme (scheme 3) with two peaks, of which the former is sharply increased and mainly used to produce angular impulse (see Fig. 7). With the new focusing field, the beam quality at the exit of linac is also almost the same as that of scheme 1.

The advantage of scheme 3 is that less excitation current is needed. The excitation current is defined as

$$I_{exc}=\frac{1}{\mu_0}\int_{start}^{end}B_z dz \qquad (6)$$

Calculation shows the excitation current of scheme 3 is 8% less than scheme 2 and 28% less than scheme 1, which means scheme3 is the most power saving. And it is proved that the more remanent angular velocity is, the smaller magnetic field of the latter peak is needed.

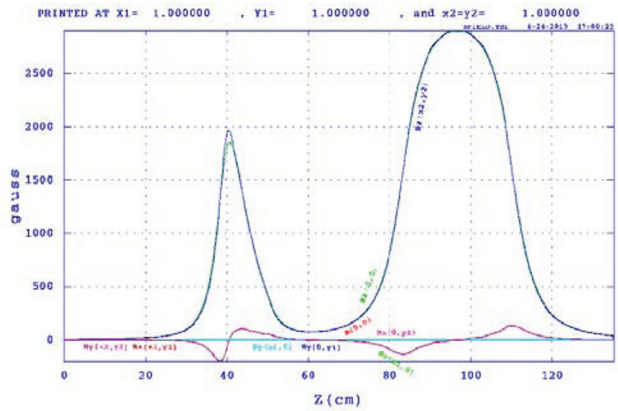

Figure 7: Magnetic field distribution of scheme 3.

However, it should be noted that the engineering layout of scheme 3 would be a bit more difficult than scheme 2 as two independent solenoids are needed. The former solenoid may be turned into a magnetic lens to produce the sharp-increased and asymmetric field. The complexity in engineering design is a drawback of this new scheme, which is still attractive if an easier method is found to achieve the asymmetric distribution.

CONCLUSION

Space-charge effect estimation is an efficient way to optimize the focusing field of the linac. For the input beam generated by EC-ITC RF gun, the focusing field mainly affects the spot size and the phase space. With the optimized magnetic field, the lens is removed and the beam radius decreases monotonously, which makes maximum use of the focusing field. 3-ps-length (FWHM) pulse containing 200pC electrons can be obtained at the exit of linac and the corresponding RMS emittance and RMS radius are 7 πmm·mrad and 0.25 mm, respectively. An alternative scheme that needs less excitation current is characterized by two peaks, of which the former is sharp-increased and asymmetric.

REFERENCES

[1] HU Tong-ning et al., Physical design of FEL injector based on performance-enhanced EC-ITC RF gun. Chinese Physics C. Waiting to be published.

[2] Luca Serafini. Envelope analysis of intense relativistic quasilaminar beams in rf photoinjector: A theory of emittance compensation. Physical Review C. Vol. 55, No. 6. June, 1997

[3] Pei Yuan-ji. Fundamental knowledge on linear electron accelerator. Internal lecture notes. 2011.

[4] B. Qin, et al., Design consideration for a hybrid undulator applied in a terahertz FEL oscillator. Proceeding of the 2012 International Particle Accelerator Conference. 2012

[5] LIU Sheng-guang. Analysis of emittance compensation and simulation results to photo-cathode RF gun. Nuclear Physics Review. Vol. 19, No. 3. Sep., 2002.

ISBN 978-3-95450-122-9