A permanent magnet electron beam spread system used for a low energy electron irradiation accelerator *

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Abstract: The development of irradiation processing industry brings about various types of irradiation objects and expands the irradiation requirements for better uniformity and larger areas. This paper proposes an innovative design of a permanent magnet electron beam spread system. By clarifying its operation principles, the author verifies the feasibility of its application in irradiation accelerators for industrial use with the examples of its application in electron accelerators with energy ranging from 300 keV to 1 MeV. Based on the finite element analyses of electromagnetic fields and the charged particle dynamics, the author also conducts a simulation of electron dynamics in magnetic field on a computer. The results indicate that compared with the traditional electron beam scanning system, this system boosts the advantages of a larger spread area, non-power supply, simple structure and low cost, etc., which means it is not only suitable for the irradiation of objects with the shape of tubes, strips and panels, but can also achieve a desirable irradiation performance on irregular constructed objects of large size.

Key words: permanent magnet spread system, irradiation, accelerator, finite element analysis, beam dynamic, uniformity

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1 Introduction

Irradiation processing has been widely applied in industries of manufacture, agriculture, bio-medicine and environmental protection because of its energy saving and environmentally friendly advantages [1, 2]. An electron irradiation accelerator, with its benefits of controllable energy, operational efficiency, no radioactive pollution source, and no energy consumption when the machine is cut off, etc, has been widely adapted in the irradiation processing industry [3, 4].

A high voltage electron accelerator mainly consists of an electron gun and an accelerator tube that is followed by a scanning magnet system, which usually uses a dipole electromagnet with a saw tooth wave energy supply [5], as shown in Fig. 1. When the electron beam passes through this system, the dipole electromagnet scans the beam in the transversal direction like the row scanning of a TV set. The under beam device drives the materials to pass the electron beam at a uniformed speed in the longitudinal direction similar to the frame scanning of a TV set [6].

The advantage of this system is that the magnet current can be adjusted according to the energy of electrons [7, 8]. However, its shortcomings are that the scanning electromagnets consume power. Besides, as the electron beam is swept by the current in the transversal direction, which actually repeats the movement along a line, the titanium window might be overheated and partially melted occasionally, especially at both ends. Actually, the most difficult and inevitable problem in the actual operation of the current scanning system comes from the fly back. As for each wave-formed power being applied, there would be a repeated beam current movement at each end of the titanium window, which may reduce the effective irradiation area on one hand while lessening the use durations of the titanium window on the other hand. Thus engineers actually have to replace the titanium window every three to six months [9]. Third, the irradiation uniformity in the longitudinal direction might also be restricted by the transportation belt speed [10].

The permanent magnet system proposed in this paper spreads the electron beam bunch in the radiation area uniformly [11, 12]. In order to achieve this purpose, two sets of magnets are introduced to let the left half of the beam bunch spread evenly toward the left side and

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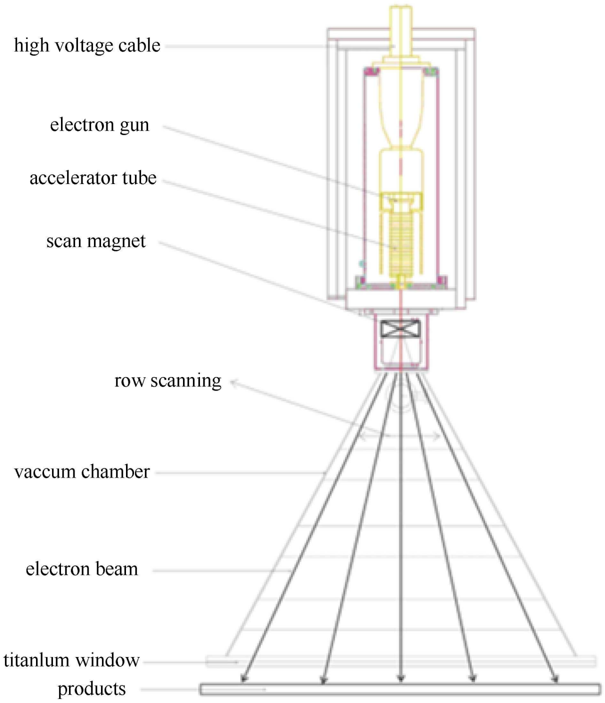

Fig. 1. High voltage electron accelerator with a beam scanning device.

the right half of the bunch to the right. One of the originalities of this design is the optimization of the permanent magnet arrangement that realizes the uniformed beam distribution in radiation area.

2 Theoretical principle

Considering the relativistic effect, an electron's mass is decided by Eq. (1).

$$m=\frac{m_0}{\sqrt{1-\beta^2}}=m_0\gamma, \tag{1}$$

in which m_0 is the rest mass of electrons, $\beta=\dfrac{v}{c}$ is the electron relative velocity, v is the velocity of electron, c is the velocity of light, $\gamma=\dfrac{1}{\sqrt{1-\beta^2}}$ is the relativity factor.

The deflecting force of electrons in the magnetic field can be expressed by Eq. (2)

$$\boldsymbol{F}=e\boldsymbol{B}\times\boldsymbol{V}, \tag{2}$$

in which $\boldsymbol{F}$ is the deflecting force, $\boldsymbol{B}$ is the magnet field and $\boldsymbol{V}$ is the velocity of electrons. When the electron energy is close to 1 MeV, its velocity $\boldsymbol{V}$=0.97c (which is close to the velocity of light, c is the velocity of light). That means the velocity of the electron with an energy higher than 1 MeV shows very small changes. When the energy of electrons with an energy lower than 1 MeV changes, the changes of the electrons' velocity are shown in Table 1.

Take the 300 keV and 400 keV accelerator electron for example. When the $\boldsymbol{V}$ changes between ±3% regions, according to Eq. (2), the change of $\boldsymbol{F}$ is limited to between ±3% regions. Thus the changes of the force on the electron and the spread width are also limited to between ±3% regions if the electron energy changes from 300 keV to 400 keV. This brings about a possibility of a set of permanent magnets that satisfies all the requirements of a 300 keV to 400 keV electron beam with a satisfactory spread uniformity and spread width kept between ±3% regions.

Table 1. Velocity of electrons of different energy.

energy/keV	velocity
300	0.8199c
400	0.8734c
500	0.9075c
600	0.9301c
700	0.9457c
800	0.9568c
900	0.9649c
1 MeV	0.9711c

According to the charged particle dynamics,

$$\frac{\mathrm{d}(m\boldsymbol{V})}{\mathrm{d}t}=e\boldsymbol{B}\times\boldsymbol{V}, \tag{3}$$

where $\boldsymbol{B}$ refers to the density of magnetic induction, e refers to the electron charge and, $\boldsymbol{V}$ refers to the electron velocity. If a Cartesian coordinate is used, Eq. (3) will be written as

$$\begin{cases} \mathrm{d}(mv_x)/\mathrm{d}t=qv_yB_z-qv_zB_y, \\ \mathrm{d}(mv_y)/\mathrm{d}t=qv_zB_x-qv_xB_z, \\ \mathrm{d}(mv_z)/\mathrm{d}t=qv_xB_y-qv_yB_x. \end{cases} \tag{4}$$

In Eq. (4), the subscript refers to x, y and z components. By applying the four order Ruge-Kutta's numerical integration, the equation can be solved numerically [13, 14].

The deflecting distance S of electrons will be calculated by Eq. (5),

$$\boldsymbol{F}=m\boldsymbol{a},\ \ S=\int_{t_2}^{t_1}at\mathrm{d}t,\ \ t=\frac{L}{V_z}. \tag{5}$$

In this equation, $\boldsymbol{a}$ is the acceleration of electron, L the height of the scanning box, and $\boldsymbol{V}$ the velocity along the z-axis direction. The velocity changes in a limited region, which means the distance of the electron deflection is limited in a small region. This theoretically justifies that a permanent magnet combination may satisfy the requirements of different energies. To prove the compatibility of the proposed spread system, the low energy accelerators are divided into three groups (300 keV/400 keV, 400–600 keV, 600–1000 keV), which are based on 5% of different $\boldsymbol{V}$.

3 Numerical simulation of the permanent magnet spread system

If the energy of accelerated electron beams to be spread is 300 keV with 1 cm radius cross section, and 22.5 πmm·mrad emittance, which is the most common case for low energy electron irradiation accelerators at present, a Cartesian coordinate system is used. The z direction refers to the mean direction of propagation of the electron beams pointing out of the paper. Both the Gaussian and uniform distributions of the initial electron beam bunch are supposed in the simulation. The beam bunch is located in the center of the magnet equipment and enters the magnetic field at the very beginning. The Gaussian and uniform distributions of the electron are respectively shown in Fig. 2(a) and Fig. 2(b).

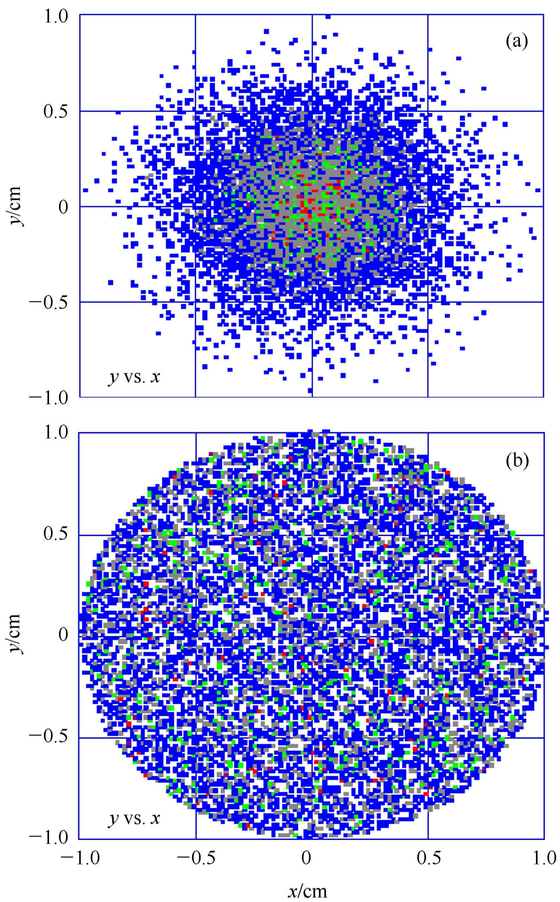

Fig. 2. The Electrons' Gaussian/uniform distributions. (a) The Gaussian distribution; (b) The uniform distribution.

One permanent magnet combination is used to simulate the beam dynamic of both distributions. The priority has been given to the Gaussian distribution case since it is a little more difficult to spread the middle part of the bunch where the higher density electron is concentrated. After the modification is optimized, the uniformity of the electron bunch is achieved for both the Gaussian and uniform distributions as shown in Fig. 7.

3.1 The magnetic field analysis of the permanent magnet spread system

The spread system consists of 2 permanent magnets. They are 1 cm apart. The first magnet is used to spread the electron beam bunch. The second one is used to improve the distribution in four-corner areas of the bunch. The first magnet consists of 4 yokes. DT4 pure iron is used for the magnetic yoke and the rare earth permanent magnet material Nd-Fe-B for the poles as shown in Fig. 3(a) and Fig. 3(b).

The ideal distribution of electrons requires the poles of both the right and left side to have minimized clearance. However, if the two poles were too close, the magnetic flux leakage (MFL) would increase through the magnet sides, thus the peak field would be reduced.

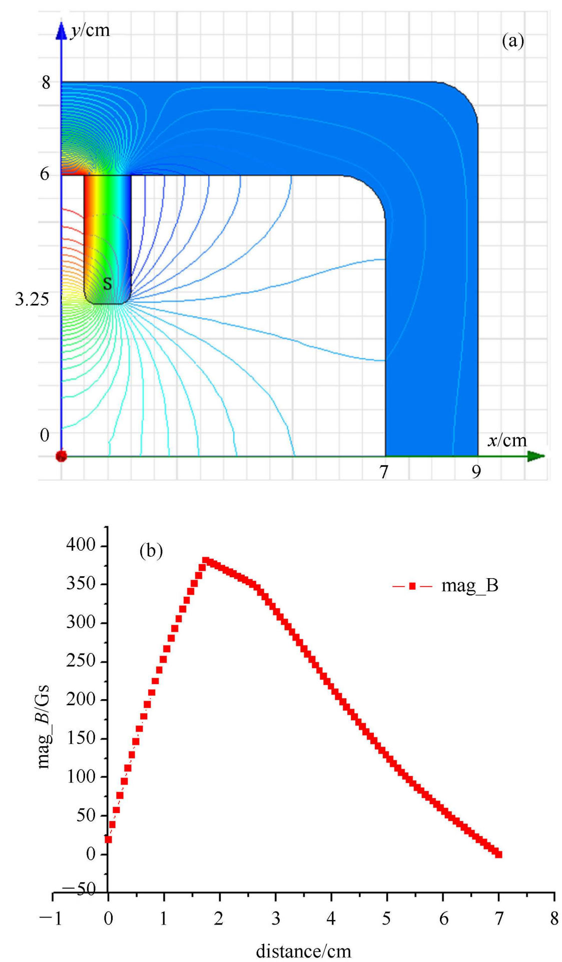

Fig. 3. The magnetic field of the first magnet. (a) The magnetic field distribution; (b) The magnetic field distribution curve.

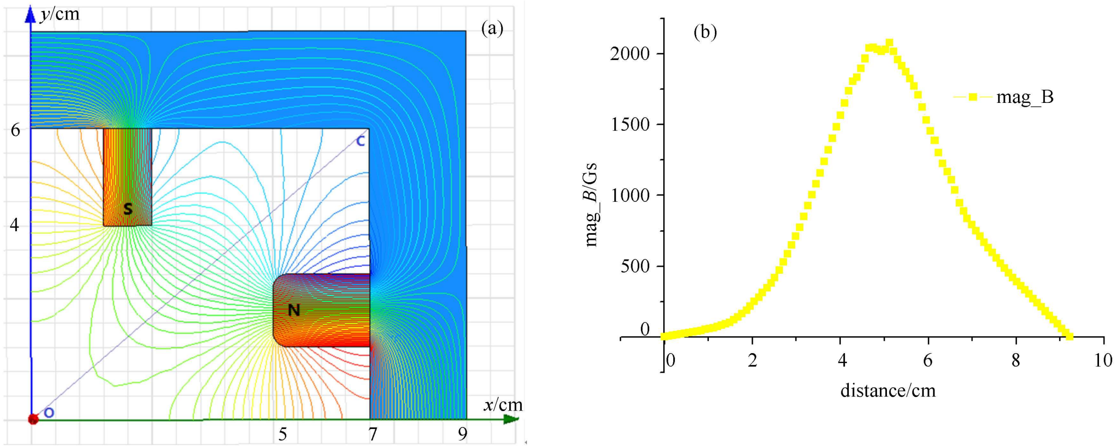

Fig. 4. The magnetic field of the second magnet. (a) The magnetic field distribution; (b) The magnetic field distribution of segment EF on the second supplementary magnet.

According to theoretical analysis, the changes of clearance and length of the poles will cause remarkable effects on the magnetic field.

The magnetic field distributions based on finite element method analysis alone in the x direction are shown in Fig. 3(b). The maximum peak value is about 380 Gs at a point of 1 cm to the center. This proposal has considered the effect of the clearance of poles on the magnetic field and aims to make the peak value as close to the center as possible, without causing unnecessary magnetic flux leakage.

The second magnet is introduced to improve the four corners' distribution of the electron bunch, as shown in Fig. 4.

The second magnet consists of eight poles as shown in Fig. 4(a). The magnetic field distributions based on the finite element method analysis alone in the x direction are shown in Fig. 4(b). The maximum peak value is around 2000 Gs at a point of 6.5 cm to the center.

3.2 Beam dynamics analysis

A. Beam dynamics analysis for permanent magnet spread system

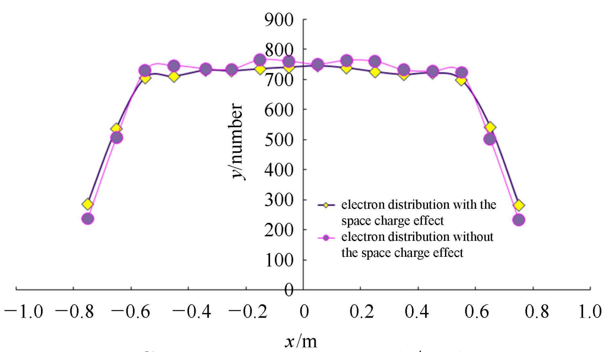

Fig. 5. Comparing curves with/without space charge effect.

PARMELA is used to simulate the dynamics of the electron beam. The space charge effect has been considered. An electron beam bunch with 10 thousand electrons was introduced to see the space charge effect on the electron beam. The results show the distribution of electrons is not obviously affected by the space charge

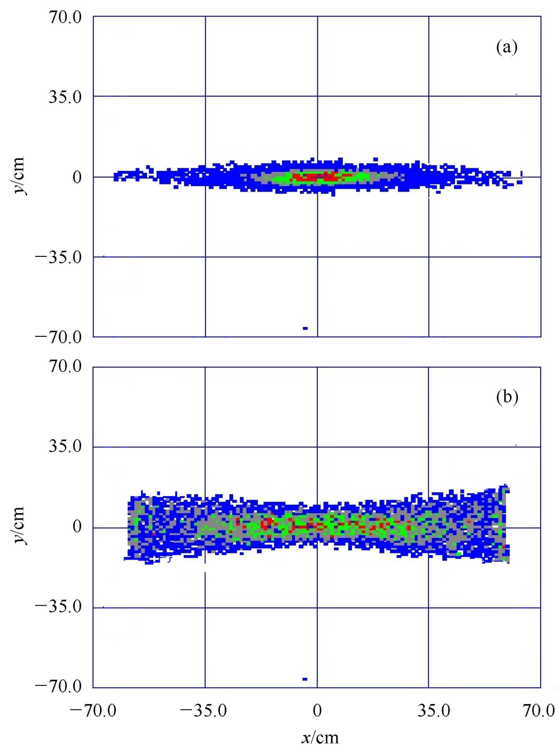

Fig. 6. The beam distribution after the first and second set of magnets respectively. (a) The result of the electron beam bunch after passing through the first magnet; (b) The spread of the beam bunch after passing through the modified two sets of magnets.

effect in our case [15]. The distribution is shown in Fig. 5. It is difficult to see the difference.

The distribution of electrons after the electron bunch passed through two magnets is showing in Fig. 6. The second magnet improves the distribution in the four-corner areas of the bunch.

The simulation is used to see how the spread system works at both Gaussian distribution and uniform beam distribution. The results are shown in Fig. 7(a) and 7(b).

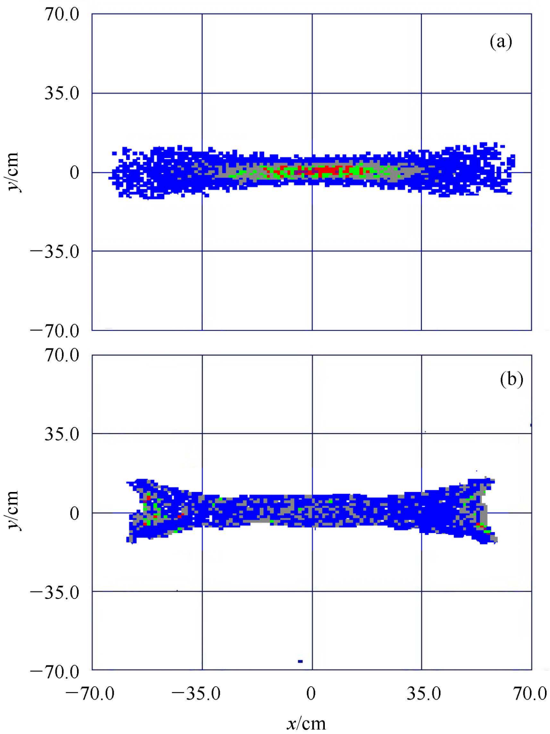

Fig. 7. Beam dynamic analysis for Gaussian/ uniform distribution. (a) The gaussian distribution of electron beam bunch passing through the spread system; (b) The uniform distribution of electron beam bunch passing through the spread system for uniform distribution.

Along the x direction, the spread region is divided into 14 sub-regions with equal width. By counting the amount of electrons in each sub-region, the uniformity can be obtained by $\rho=\frac{N_{\max}-N_{\min}}{N_{\max}+N_{\min}}$, in which $N_{\max}$ is the maxim number of electrons in the radiation area and $N_{\min}$ is the minimum.

The result shows that the electrons are uniformly distributed in a rectangle area with a length of 1.2 m and a width of 0.1 m, the lateral uniformity is $\leqslant$7.1%.

According to Fig. 7(b), the result suggests that the electrons are uniformly distributed in a rectangle shape with a length of 1.2 m, a width of 0.1 m and the lateral uniformity of vertical integral is $\leqslant$6.5%. The results have proved that the spread system is applicable for the two initial electron beam bunches.

B. Feasibility of electron beam permanent magnet spread system used in a low energy accelerator

In order to verify the compatibility of the system in the energy range from 300 keV to 1 MeV, dynamics simulations of the system of different electron energies, namely, 300 keV/400 keV, 400 keV/600 keV, 600 keV/1 MeV, were carried out.

The spread system of the same pole with positions being slightly adjusted was used in this beam dynamic simulation. The results are shown in Fig. 8–Fig. 10.

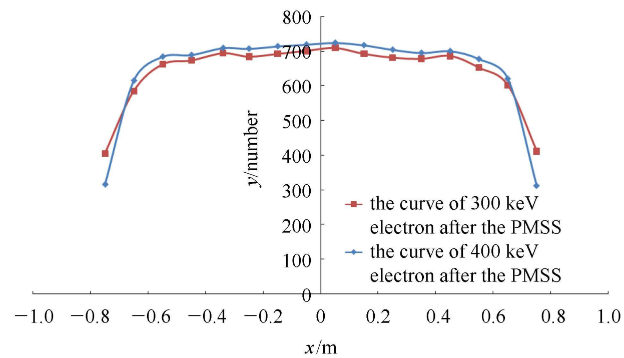

Fig. 8. Comparison between the curves of 300 keV/400 keV electron beams.

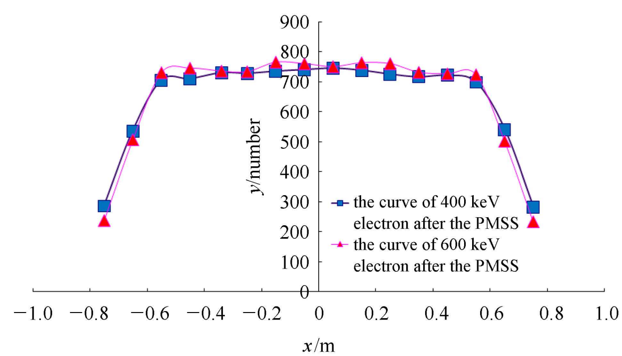

Fig. 9. Comparison between the curves of 400 keV/600 keV electron beams.

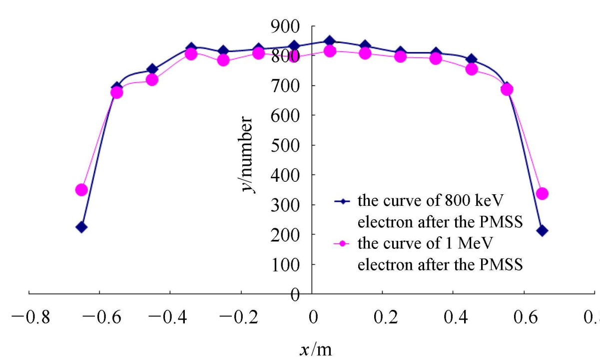

Fig. 10. Comparison between the curves of 600 keV/1 MeV electron beam.

Radiation uniformity of the ordinary scanning system usually is around 10% and the scan area is 1200 mm (length) and 130 mm (width), while the radiation uniformity of the permanent spread magnet is less than 6.7%, better than the national standard 10%. The results show that the permanent magnet spread system can be easily adopted in low energy accelerators.

4 Conclusions

The proposed permanent magnet spread system remarkably improves the spread uniformity. As the spread area in the longitudinal direction could be enlarged, it might be used not only for wires, strips and panels irradiation, but also for irregular structured objects of large size. This paper not only verified the excellence of the proposed system in improving the spread width and uniformity but also proved that the same uniformed spread of electron beam in a low energy electron irradiation accelerator of different energy levels could be achieved. Thus, the permanent magnet spread system is both practicable and applicable for low energy electron irradiation accelerators.

References

1 Chmielewski A G, Haji-Saeid M. Radiation Physics and Chemistry, 2014, **71**(1–2): 17–21

2 Emerging Applications of Radiation Processing. IAEA-TECDOC-1386, April, 2003

3 ZHENG Shu-Xin, TANG Chuan-Xiang et al. Chinese Physics C, 2008, **32**(3): 228

4 LIU Hua-Chang, WANG Xiu-Long, FU Shi-Nian. High Energy Physics and Nuclear Physics, 2006, **30**(6): 581 (in Chinese)

5 WANG Xiang-Qi, XU Yu-Cun et al. Nuclear Techniques, 2008, **31**(6): 441; YANG Jun, LI Dong et al. Calculation and Design of a High Voltage Electron Accelerator. Proceedings of IPAC'10, Kyoto, Japan, MOPEB074

6 Sanelli C, Voelker F et al. Specification of Power Supplies for Eight Scanning Dipole Magnets of the CNAO Project. CNAO internal Spec., CNASP-DF-007WXX-03018

7 FENG De-Ren, WANG Xiang-Qi et al. High Power Laser and Particle Beams, 2008, **20**(4) 593–596 (in Chinese)

8 REN Xiu-Yan, LU Yu-Zhu. Atomic Energy Science and Technology, 2011, **45**(7): 868 (in Chinese)

9 According to a Meeting with Xianghua Zhang, a senior engineer and the director of Wuxi EL Pont Group, held in Huazhong University of Sicence and Technology. WUHAN, at July, 2013, 18

10 MO Yan, ZHANG Xing-Bao, ZHANG Ya-Qun. J. Radiat. Res. Radiat. Process., 2006, **24**(1): 59–60

11 YUAN Qin-Liang, WANG You-Zhi et al. High Energy Physics and Nuclear Physics, 1987, **11**(1): 15 (in Chinese)

12 Novitski I, Zlobin A V. IEEE Trans. Appl. Supercond., 2007, **17**(2): 1059–1062

13 Bogacki P, & Shampine L F. Appl. Math. Lett., 1989, **2**: 1–9

14 Luna H B. Luna Nuclear Instruments and Methods in Physics research A, 1989, **285**: 349

15 YANG Jian-Jun, ZHANG Tian-Jue et al. High Energy Physics and Nuclear Physics, 2007, **31**(8): 769 (in Chinese)