Design Study on the Electron Accelerator Ridgetron for Material Irradiation

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Abstract. Irradiation processing has been widely used in industrial production, such as curing, cross-linking of polymers and preservation of food. A Ridgetron for material irradiation processing is studied in this paper, with output energy of 2.5 MeV. Overall description on the Ridgetron acceleration prototype, bending magnet design and optics calculation are introduced in the paper. The beam dynamics simulation and the particle trajectory calculation respectively ensure the beam focusing and parallel beams.

1. Introduction
In recent years, irradiation processing has been widely used in industrial production, such as curing, cross-linking of polymers, sterilization of medical disposables, preservation of food, and so on [1]. The radiations used in irradiation processing mainly are Gamma rays, X-rays and electron beams. Usually, the maximum electron beam energy for industrial irradiation is 10 MeV to avoid the activation of the irradiated materials. For this energy, many electron linear accelerators (linac) have been widely used for electron beam irradiation. However, they are operated in pulse mode and with low energy efficiency [2, 3].

In addition to the acceleration energy, the accelerators to be installed in industrial facilities also need to satisfy the requirements of compact size, low power consumption and stable operation. The DC accelerator can be very compact in the energy under 300 keV. However, it is large to prevent the discharge of an acceleration column in the energy over 300 keV. In 1989, J.Pottier proposed the recirculating accelerator concept and designed the first Rhodotron which could accelerate the continuous beams of the 0.5-10 MeV range in a compact space [4]. Since then, Japan developed a Ridgetron [5] and South Korea developed a Fantron with the similar principle [6, 7]. Since the acceleration voltage per pass is chosen relatively low, the heat loss of the acceleration cavity can be kept small, even in continuous operation.

A Ridgetron with the final energy of 2.5 MeV is studied in this paper for material irradiation processing. It mainly consists of a cylindrical cavity resonator, small bending magnets and an electron gun as shown in Figure 1. After overall description on the Ridgetron acceleration prototype, this paper
mainly focuses on the bending magnet design, which is crucial for the system stability. The beam dynamics simulation and the particle trajectory calculation should respectively ensure the beam focusing and parallel beams. Finally, the simulation result shows that the beams can be accelerated up to 2.5 MeV stably, which confirmed the feasibility.

2. Overall description of the Ridgetron prototype

As shown in Figure 1, Ridgetron is mainly composed of a cylindrical cavity equipped with two hollow ridges, four bending magnets at its periphery and an electron gun. After being focused with a solenoid coil, the beams extracted from the electron gun are injected into the acceleration cavity. Then the accelerated beams pass through the cavity in the radial direction and are deflected by bending magnets for recirculating acceleration.

The overall size of the machine is defined by the operating frequency, which related to the size of RF cavity and the availability of power tubes. As the energy gain per pass is limited at 0.5 MeV to keep down the power loss, the beams have to pass the acceleration gap five times with the four bending magnets to achieve the final energy of 2.5 MeV.

3. Bending magnet design

The bending magnets play two important roles in the prototype: beam focusing and parallel beam deflection. The beam focusing is performed with the edge focusing of the bending magnets equipped with an active inverse field clamp which can excite an inverse field as shown in Figure 2. The geometrical edge angle and inverse deflection angle are two main parameters which contribute to the vertical focusing. A good combination of the angles should both satisfy the compact engineering consideration and beam focusing requirement. With the particle trajectory calculation, the beams after deflection should be parallel to the initial beams under a suitable current ratio of sub and main coils.

3.1. Bending Magnet Design consideration

A sector dipole has weak focusing in the horizontal plane (x direction in Figure 1) and can be considered as a drift in the vertical plane(y direction in Figure 1). For rectangular dipoles, where the entrance and exit angles of particle trajectories are not perpendicular to the dipole edge, there is an edge focusing/defocusing effect in the vertical plane due to the edge angle. The edge focusing is
widely used for dipoles design in beam line. In the first-order matrix description, the magnetic fields are approximated by constant rectangular areas (hard edge approximation). For an actual magnet, the fringing field should be taken into consideration instead of hard edge approximation, which will decrease the edge focusing force in the vertical plane [8].

In our case, the excessive increase of the edge angle is not desirable for small magnets of the Ridgetron for engineering considerations. To achieve effective focusing in both planes with an acceptable small edge angle, we adopt a scheme with an inverse field clamp in the front of the main bending magnet to ensure enough vertical focusing. The inverse field clamp consists of a clamp iron and a sub-coil to excite an inverse magnetic field. In order to better explain the angles definition, we draw a beam trajectory schematic diagram of one bend pass with hard edge approximation. As shown in Figure 2, $\theta$ is the geometrical angle between the edge and x direction, $\alpha$ is the inverse deflection angle between the particle velocity and z direction at the exit of the inverse field clamp. The coordinate system is Cartesian coordinate system and the origin point P is chose at the center of the inverse field clamp entrance.

According to the angles definition in Figure 2 and the edge focusing principle, the geometrical edge angle $\theta$ can generate a vertical focusing at the entrance of the inverse field clamp. The inverse deflection angle $\alpha$ due to the inverse field integral value must be bigger than the geometrical edge angle $\theta$, as a result, a positive $\beta$ can generate vertical focusing at the entrance of the main bending magnet too. Considering the engineering realization, the geometrical edge angle $\theta$ should be as small as possible, better within 3 degree.

Because the interval between the two parallel particle trajectories is designed to be 14 cm to ensure the bending magnets can be placed side by side as shown in Figure 1, what is more, the curvature radius of the bending magnet becomes larger for the initial deflection in reverse direction. Therefore, the inverse deflection angle $\alpha$ is limited by the homogeneous field area of the main bending magnet. It is a challenge to find a suitable collocation of the edge angle and inverse deflection angle, with the considerations of beam optics and engineering realization.
3.2. Bend Magnet model

The main parameters of the bending magnet are listed in Table 1, and Figure 3 shows the magnet model simulated by TOSCA.

Once the geometrical magnet size is determined, the only adjustable variables are coils current, which should satisfy both the vertical focusing requirement and the parallel beam condition. In our case, the final geometrical edge angle at the entrance and the exit of all magnets is 3°. There are four bending magnets for different energy with the same structure size but different current sets. As the beam optics is same with the same particle trajectories for different beam energy, so the particle trajectories are kept the same by adjusting coil currents.

Table 1 The main parameters of the bending magnet

| Parameter                      | Value          |
|--------------------------------|----------------|
| Main bending magnet radius     | 100 mm         |
| Vice inverse clamp thickness   | 30 mm          |
| Geometrical edge angle         | -3°            |
| Gap between clamp and bend     | 45 mm          |
| Gap between poles (up and down)| 20 mm          |
| Magnet height                  | 360 mm         |
| Cross section of Sub-coil      | 80mm*6mm       |
| Cross section of main-coil     | 80mm*15mm      |
| Trapezoidal step thickness     | 0.6 mm         |
| Trapezoidal step radius        | 95-100 mm      |

For the compact consideration, the homogeneous field area of the main bending magnet is an important parameter to achieve a bigger inverse deflection angle. As the deflection radius is about 80 mm, considering the beam size, the radius of homogeneous field should be controlled over 90 mm. We added a small trapezoidal step with thickness of 0.6 mm at the bending magnet outer radius of 95-100 mm to improve the outer radius magnetic field. Finally it can achieve 0.06% within the radius of 80 ±10 mm area.

4. Beam optics calculation

As shown in Figure 4, the beams are deflected in reverse direction so that they can enter the main bending magnet with an enough positive edge angle β to ensure the vertical focusing. To be more accurate in beam optics, we calculate the fringing field effect with subdivision method. Effects of the fringing field were studied sufficiently by dividing the fringing field region into small segments.
transverse to beam trajectory. The field inside each segment is replaced by a uniform field with hard edge approximation in the beam optics calculation, and the normalized magnetic field subdivision result in beam optics calculation is shown in table 2. Since the planned beam current is modest, the space charge effect may not be excessive. The beam optics result calculated by MADX which based on transfer matrix is shown in Figure 5.

Table. 2 Magnetic field subdivision result of half section for 1 MeV

| Segment number | Segment length(mm) | Normalized magnetic field | Deflection angle(deg) | Deflection radius(mm) |
|----------------|--------------------|----------------------------|-----------------------|-----------------------|
| 1              | 289.2              | -0.0116                    | -2.3930               | 6925.6                |
| 2              | 14.9               | -0.2279                    | -2.4203               | 352.5                 |
| 3              | 12.5               | -0.2721                    | -2.4237               | 295.2                 |
| 4              | 18.6               | -0.1794                    | -2.3786               | 447.8                 |
| 5              | 22.1               | 0.2745                     | 4.3229                | 292.7                 |
| 6              | 7.8                | 0.8015                     | 4.4555                | 100.2                 |
| 7              | 6.5                | 0.9647                     | 4.4690                | 83.3                  |
| 8              | 6.3                | 0.9962                     | 4.4728                | 80.6                  |
| 9              | 114.8              | 1                          | 81.8954               | 80.3                  |

Figure. 4 The subdivision of magnetic field along the beam trajectory
5. Conclusion
A new cw electron Ridgetron for irradiation processing is studied in the paper, which can accelerate continuous beams to 2.5 MeV in a compact space. The bending magnets with fringing field and active inverse field clamps were introduced to increase the vertical focusing. The beam trajectory and beam optics calculation methods were discussed. In the simulation study, the electron beams can be accelerated successfully and stably up to final energy. The space charge effect was not included in this calculation for the modest beam current.

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