Electromagnetic Electron Irradiation Field Shaping Systems for Industrial High Voltage Accelerators

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The electron irradiation field shaping system (IFSS) of industrial accelerators with an accelerated beam energy in the range from 0.3 to 4 MeV is traditionally made as a triangular vacuum chamber with a foil outlet window situated on one of its sides. An accelerated electron beam is input into the vacuum chamber through the opposite angle and is scanned over the outlet window foil creating an electron irradiation m field on a treated object. Usually the distribution uniformity of a linear electron beam current along the outlet window is not more than $\pm 10\%$, that is sufficient for the majority of commercial electron beam technologies. The upper bound of $\pm 30^{\circ}$ is, as a rule, set on the beam scanning angle because of the increased energy losses. If the axis of the accelerating structure is directed vertically and the above mentioned shaping system is used, the total height of the accelerator, for example with an energy of 1 MeV and the outlet window width of 2 m, is about 6 m, requiring higher premises to provide its proper maintenance. Large vertical dimensions of such machines often is an obstacle on the way to their commercialisation and it noticeably narrows the market of potential consumers. In the case when the accelerating axis is horizontal, the vertical sizes do not exceed 2 m and no hoisting mechanisms are needed for the accelerator maintenance (e.g. - cathode replacement).





However, the use of the conventional IFSS allows to irradiate only the materials moved in the vertical plane, such as flexible or free-flowing ones, what is dictated by the horizontal direction of the outlet electron beam. Machines with the 90° turned and conventionally scanned beam are known but the result is the same - the growth of overall dimensions.

Proposed several years ago IFSS with the scanned beam turning by an angle of about 90° allows to decrease appreciably dimensions of the installations for radiation processing. Such system for the irradiation electron field shaping with an extended turning magnet (IFSSM) is schematically shown in Fig.1. The decrease in sizes in such a design is achieved due to the combining of two functions (turning + irradiation field shaping) in one and the same unit. As the outlet window length in the accelerators for electron beam technologies is, as a rule, in the range between 1 and 2 m, and the window width is about 10 cm, the ratio of the turning magnet aperture length to its width is in the range from 10 to 20. The poles cross-section with no iron saturation for accelerators with energy up to 4 MeV is estimated to be not more than several tens of square centimetres, thus the magnet has a form of highly elongated frame.

As Fig.1 shows, the main peculiarity of the IFSSM as an electron optic system is that more then 90% of electron paths from the scanning device to the outlet window foil lies outside the magnet aperture at a sufficient distance from its poles, where the magnetic field distribution is highly nonuniform. However, it is this area where the shaping of the electron beam irradiation field takes place. With the aim to study the IFSSM characteristics thoroughly and to get the possibility of its design optimisation, a numerical model of the IFSSM has been developed [1]. The calculation of the three-dimensional magnetic field distribution for such a system is a rather complicated task. Therefore, taking into account the above mentioned peculiarity of the magnet geometry, two-dimensional calculations of magnetic field have been performed (in the transverse XY plane) with the following extrapolation of magnetic induction values to the nodes of the three-dimensional mesh for the trajectory analysis. Numerical simulations have been performed simultaneously with the investigation of the IFSSM on a fullscale model of 1.6 m length installed at the exit of the 300 keV electron accelerator. Comparison of the numerical simulation results with experimentally gained data confirmed the fitness of the created numerical model to the actual IFSSM with an accuracy sufficient for performing engineering calculations. Thus in the YZ plane of symmetry the discrepancy between calculated and measured values of magnetic induction is within the limits of the measurement error (1 G). As the numerical simulations and measurements of the IFSSM characteristics show, the given design allows to decrease the amplitude of the beam scanning along the outlet

window to a value of $\pm 10^{\circ}$. The angles of the electron trajectories on the outlet window foil are $90\pm7^{\circ}$ over its whole length (1.5 m).



Figure 2. The projection of electrons trajectories on the XY plane for particles deflected by 2.5° in the transverse direction and in the longitudinal direction according to Fig.1.

Shaping of the uniform distribution of the electron beam current across the outlet window is the most difficult problem in such a design, as there are focusing forces influencing all the charged particles deflected from the longitudinal symmetry plane of the magnet. Moreover, as it is typical for all cylindrical optic systems, the focus location is changed along the magnet length. Projections of the electron trajectories, deflected in the transverse direction (X), are shown in Fig.2.



Figure 3. The self-shielded 300 keV electron accelerator equipped with the IFSSM at the Glukhovo textile plant.

The almost constant width of the beam, scanned over a foil through the whole length of the window, may be obtained both by corresponding modulation of the inlet scanning angles of electron transverse deflections, as well as by local correction of the turning magnet field. The image of the electron beam is enlarged in the longitudinal direction over the outlet window length proportionally to Z coordinate. So, for the obtaining the most uniform distribution of the linear beam current it is reasonable to focus the beam to the farthest edge of the window by means of an inlet magnetic lens. As may be seen from Fig.1, the height of the IFSSM is about 1/3of the outlet window length, making possible the installation of electron accelerators with the IFSSM practically to any production area. This also allows to design rather extended outlet windows, if necessary. Another important merit of the IFSSM in comparison with conventional IFSS is providing almost normal angles of electron trajectories on the outlet window foil through all its length. Accelerators equipped with the IFSSM are easily integrated into various production lines

At present we have designed and constructed several accelerators with the IFSSM [2] for an energy range from 0.3 to 1.0 MeV. The self-shielded electron accelerator for an energy of 300 keV, beam current of 65 mA and the 1.5 m electron irradiation field width is shown in Fig.3. It has been operating on the industrial production line at the Glukhovo textile plant for several years.

Some technologies uses the double-sided irradiation of objects that allows to process materials almost twice thick in comparison with the single-sided irradiation at the same energy. With conventional IFSSM this process is carried out by means of step-by-step irradiation of the both sides of material on one accelerator, or by using two accelerators, that is not always acceptable from technological consideration.

Two design versions for the double-sided irradiation by one accelerator, equipped with a double-magnet IFSSM were considered: 1). with two outlet windows located towards each other; 2). with two windows oriented in opposite directions.

The both versions were investigated and optimised by means of numerical simulation. In the first case the electron trajectories are shaped outside turning magnets, so the electron optic characteristics are practically the same as for



Figure.4. The schematic view of the double-magnet IFSSM and projections of electron trajectories in the vacuum chamber. Angle step of the displayed trajectories is 1°.

the single magnet version. It should be mentioned that in this IFSSM design outlet windows can be additionally heated by

an electron beam extracted from the opposite window and the scanning angle only for the beam transfer from one window to another exceeds $\pm 10^{\circ}$.

Modelling of the magnetic field distribution in the second case had been made by using principles of the field superpositioning that allowed to reduce the calculation of magnetic field distribution to the operations with magnet potential arrays having been previously calculated for the single magnet version for one quadrant of the XY plane. The IFSSM like this has characteristics quite different from those studied above. Magnetic field in the symmetry plane of the magnet equals zero and grows more steeply than the single magnet field if move off this plane. Calculations have shown, that electron optic characteristics of the given IFSSM depend on the ratio of the distance between magnets (L) to the distance between their own poles (S). With this ratio decreasing less than 5+6 (i.e. with magnets closing together), the beam scanning amplitude is reduced to the critical value comparable with the beam own cross-section because of the steep growth of the magnetic field to the both sides from the plane of symmetry.



Figure 5. Schematic cross-section of the IFSSM for the double-sided irradiation of flexible materials and projections of electron trajectories in the vacuum chamber. (Only edge trajectories are shown. Arrow indicates the direction of the treated material movement.)



Figure 6. Typical oscillographic picture of current pulses in the scanning magnet winding for shaping the electron irradiation fields in two opposite outlet windows.

This makes difficult to get sufficiently homogenous distribution of the irradiation field over the extraction device. The electron projections on the YZ plane calculated for the IFSSM with a ratio of L/S=8.5 are shown in Fig.4. The valuable peculiarity of the considered IFSSM is an opportunity to locate the technological channel in the vacuum

chamber and to irradiate flexible materials as shown in Fig.5. In both design versions of the IFSSM the normal angles of electron trajectories on the foil surface are provided over the whole area of the outlet window.



Figure 7. The distribution of linear electron beam current along outlet windows for the 750 keV accelerator with double-magnet IFSSM.

On the basis of performed calculations, the IFSSM for the electron accelerator with horizontally oriented accelerating structure has been designed. The energy of the electron beam, extracted through two opposite outlet windows (each 1.7 m in length), is 750 keV and the beam current is up to 80 mA. Typical curves of the linear beam current distribution beyond the accelerator outlet windows' foil are presented in Fig.7. The measurements were done by means of a sensor of a Faraday cup-type moving along the window at a distance of 30 mm from the foil. The range of frequencies for the longitudinal beam scanning is $f_z = 400-500$ Hz and for transverse direction - $f_x = f_z / n$, where $n = 16 \div 32$.

The accelerator is equipped with a metal local radiation shielding and intended for the operation on the industrial line for producing soft roofing. The accelerator is under assembly now in one of the plants in Ivanovo. The doublesided irradiation of material is performed continuously according to a scheme shown in Fig.5. The overall height of the accelerator does not exceed 1.9 m, no hoisting and lifting devices are needed for its maintenance.

Now we have two similar accelerators under construction: one intended for soft-roofing production, and the other to be applied on the line for foamed polyethylene production.

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