# FURTHER DEVELOPMENT OF IRRADIATION FIELD FORMING SYSTEMS OF INDUSTRIAL ELECTRON ACCELERATORS

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## *Abstract*

Electron beam irradiation field forming systems where accelerated electron beam is scanned in a constant field of the elongated bending magnets were developed in our institute more than 10 years ago and have a number of advantages in comparison with traditional ones. Since than they have been applied in two accelerators with energies 300 and 400 keV; version of the similar system with two electromagnets for two-side irradiation of flexible materials – in a series of 750 keV high voltage accelerators ("Electron-10") and successfully operate now in several domestic industrial lines. Systems of forming of electron beam irradiation field based on the same principle have been used in several projects, some of them already operate. Electron optic characteristics of such systems and their various modifications as well as aspects of their possible usage are discussed in the paper.

Electron accelerators on energies from 0,3 to 10 MeV are being widely used in commercial scale in various industrial radiation technological processes. One of the determinatives assigning a price of an installation with electron accelerator is its size that is defined mainly by dimension of the accelerator itself and by a size of an irradiation field forming system.

Electron beam distraction to the atmosphere via foil outlet window in the above region of energies in all accelerators (DC high voltage or high frequency ones) is performed by scanning the beam across a foil in one or two directions. Maximal scanning angle is restricted by losses of electron energy in the window foil increasing pro rata with the angle and growing of portion of reflected from the foil electrons. In practice it does not exceed ±30°, correspondingly a ratio of the vertical dimension of vacuum chamber, where electron beam is scanned, to the outlet window length is $\sqrt{3}/2$ at least. Note, that majority of industrial production processes requires vertical direction of the outgoing beam, so size of an installation decreases on a height of the vacuum chamber.

An electron beam irradiation field forming system with extended bending magnets (IFFSM), where electrons are scanned into magnetic field of extended bending magnet placed in front of an outlet window, was developed firstly in the Efremov institute almost 20 ears ago and schematically shown in Fig. 1 [1,2].

Vertical size of the vacuum chamber here does not exceed approximately 1/3 from the outlet window length, an accelerator may be placed horizontally at the side of production line and an electron beam emerging from the outlet window is directed vertically. Beam scanning angle is in the limits of ±10°, for electrons outgoing into atmosphere the angles differ from normal to the foil plane on ±7°, i.e. electron trajectories are practically parallel. With the outlet window length in 1-2 m diapason an installation height is defined mainly by a size of accelerator.

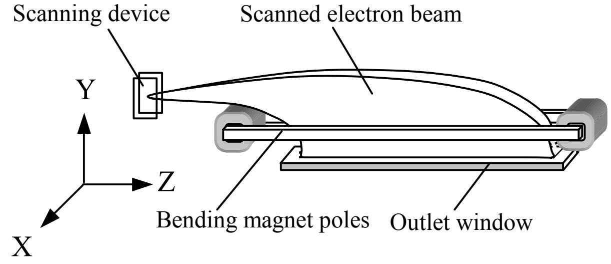

Figure 1: Schematic view of the IFFSM.

Specific feature of the IFFSM considered as an electron-optic structure is that a movement of electrons in the magnetic field, defying parameters of the irradiation field, is taking place beyond the bounds of the magnet and on a considerable distance from it. Numerical investigations of the IFFSM's properties and measurements of beam parameters have shown, that depending on electrons inlet point into the magnet field, and theirs inlet angles, in addition to bending of electron trajectories on an angle about 90°, electrons are being focused in a cross (X) direction and a focal distance depends on Z coordinate. In a longitudinal (Z) direction the IFFSM acts as non-linear magnifying lens and Y-size of the inlet beam transforms into Z-size and increases in the farthest end of the outlet window up to 20 times. These properties of the IFFSM put certain limiting requirements on the inlet beam qualities, i.e. its emittance and maximal energy spread.

The IFFSM with one outlet window and one bending magnet has been developed for a first time for DC HV accelerators with energies 300-400 keV, later on it was used by the IBA in the 10 MeV Rhodotron [1,3].

In a number of real processes it is necessary to provide two-side irradiation of material. The IFFSM allows to meet this challenge by different ways.

Constructing a magnetic field by means of several electric magnets it is possible to create two identical irradiation fields directed towards each other in Y direction, lengthy along Z and shifted corresponding each other by X, the later is necessary to avoid heating of the outlet window elements by the beam emerging from the opposite window. Such a system is the most suitable for two-side irradiation of solid materials and products.

In a case when the material is flexible (and that is a wide segment of a market of the materials processed by E-beam) a two-side irradiation can be performed as it is shown in Fig. 2. Resultant field of the two electric magnets is equal to zero in a plane of system symmetry and when electron beam is deflected from it on a small angle it naturally "slips" in one or another outlet window.

Irradiation field forming system realized by this scheme is used in a series of the HV DC accelerators with parameters 750 keV, 50 kW [2].

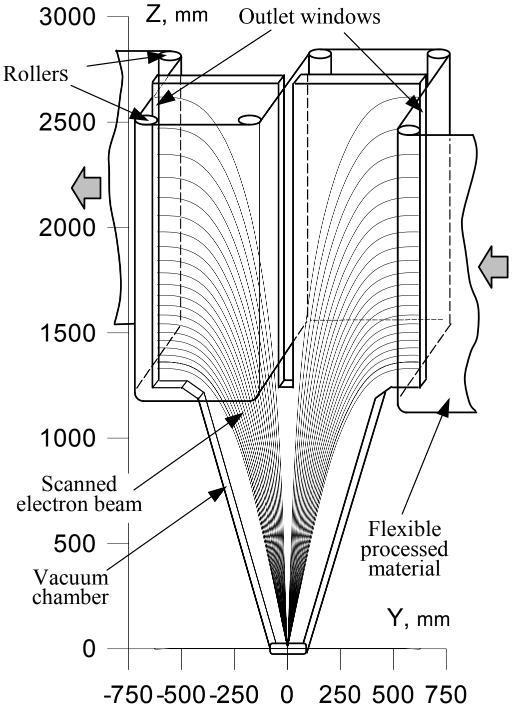

Figure 2: Schematic view of two-side irradiation of flexible materials. Bending magnets are not shown.

Another promising application of the IFFSM may lie in the field of installations generating Bremsstrahlung.

Bremsstrahlung (X-ray irradiation) has penetrability into the matter many times greater than accelerated electrons and therefore it is more attractive for sterilization of big-volume objects such as boxed food, etc. Because of possible appearance of radioactive isotopes, 10 MeV is the maximal permissible energy level authorized by legislation of majority of countries for the installations generating Bremsstrahlung and 5 MeV – for radiation food pasteurization.

At energies of accelerated electrons in the considered range (1-10 MeV), the maximum X-ray radiation release can be obtained by using a thin X-ray target made of a metal with a high atomic number (tungsten, tantalum, gold) [4].

It is known that when accelerated electrons interact with matter, part of their power (E0) is transformed into thermal power Et; part is radiated as X-radiation EX (in both directions); part is carried away by the electrons which are reflected from the surface of the target ER; and part is carried away by the electrons that transmit through the thickness of the target Ee.

The ratio of the above powers to the incident electron beam power depends on the beam energy, the target material, and its thickness. The optimal target thickness is the one that provides the maximum power release in the form of X-radiation in the forward direction. For example, when the electron beam energy is 4 MeV, the optimal target thickness is on the order of 0,7-0,8 mm. For this energy the power of the electron beam is redistributed in the following way: EX ~10%, ER ~16%, Ee ~25% while the remaining part of power is transformed into thermal one. The reflected electrons as well as the electrons that pass through the target are distributed in angle and energy. The average root-mean-square energy of the reflected electrons is somewhat lower than the half-energy of the incident electrons. For the electrons that pass through the target, the average value for the transmitted electron energy is about 0,7 MeV for an incident beam energy of 4 MeV. The electrons reflected from the target are being absorbed by elements of a vacuum chamber holding converter target that requires additional cooling of this chamber. Thus, a significant part of the beam power remains in the form of accelerated electrons (those that are reflected or have passed through the target) and eventually are lost. Note that such losses are considerably higher than the power of the electron beam that is transformed into Bremsstrahlung in the forward direction. Since the electrons that pass through the target can irradiate the surface layer of the "product" material, their removal is performed by absorbers made usually from a metal with low atomic numbers (e.g., Al) that are located after X-ray converter target. When that happens, a part of the X-radiation power up to 15% (at the energy of 5 MeV) is absorbed by the electron absorber thus decreasing the effective efficiency of the E-beam to X-ray conversion [5].

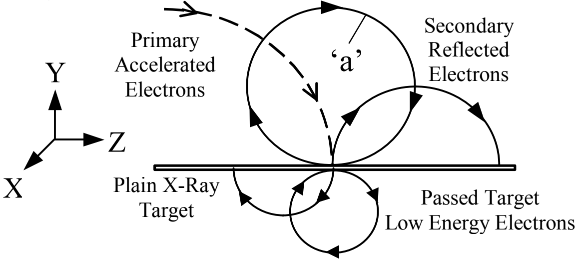

Figure 3: Schematic view of trajectories of reflected and passed through target electrons in a homogenous magnetic field.

The situation changes when an extended bending magnet is installed in front of the target: reflected electrons remain in its magnetic field and move by curvilinear trajectories. Reflected electrons will reach the surface of the target unless they do not leave the magnetic field area or hit the vacuum chamber walls. Projections of electron trajectories in a homogenous cross magnetic field with the field lines normal to the picture plane (YZ) are schematically shown in Figure 3. Tangential reflected electrons (the trajectory "a", Figure 3) will bear the maximum remoteness from the target plane. The most of reflected electrons (more than 90%) have root mean square energy lower than ½ of incidental electrons energy. Moving by trajectories with smaller radiuses than initial electrons they come back to the target, at the same time they are being focused in a cross direction (X) and return back to the system plain of symmetry. This effect is experimentally proved by an absence of heating of vacuum chamber sidewalls and the wall nearest to the scanning device in the accelerators equipped with IFFSM with foil outlet window, otherwise, the furthest wall is being heated that is followed from Fig. 3. Projections of reflected from the target electrons from a point with coordinates Y=–0,4 m, Z=1 m under different angles (with step 5°) and with energies equal to ¼, ½ and ¾ from initial electrons energy (E0) in a real (non-homogenous) field of the elongated bending electric magnet are shown in Fig. 4. It can be seen that even with energy equal to ¾ E0 the greater part of reflected electrons come back to the target plane

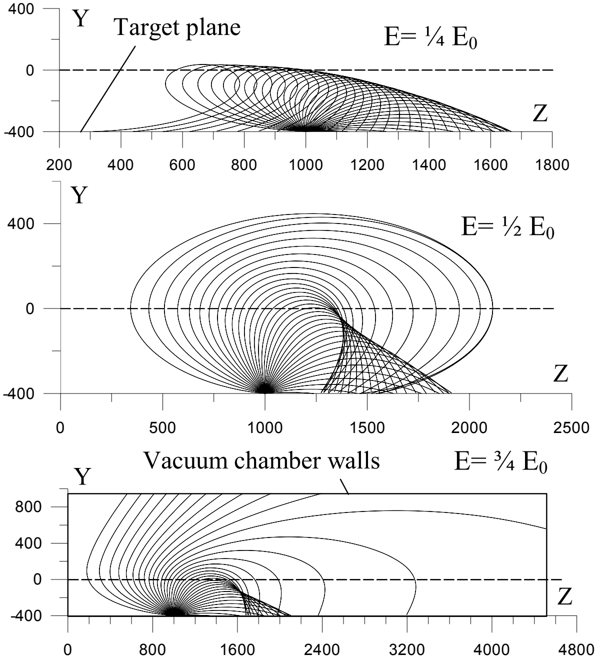

Figure 4: Projections of trajectories of electrons reflected from the point of a plain target with coordinates Y=-0,4 m, Z=1 m in a magnetic field of extended bending magnet. Y=0 corresponds to a symmetry plane of the magnet. Electrons are reflected with step 5º.

The electrons that pass through the target return back to its surface also. Since their root mean square energy is many times lower than the energy of the initial electrons, their turning radius is smaller proportionally. Because the target outer surface is faced to an atmosphere, the electrons have repeated collisions with the air molecules losing their energy and a distance of their remoteness from the target is less than if they would move in a vacuum. Therefore, if the distance between the target and the “product” material is sufficient for the electrons to turn and return back to the target (about 10-20 cm depending on energy and geometry of the magnet) there is no need for any absorbers for the electrons that pass through the target

The maximum improvement of the X-ray power can be estimated from the condition of returning of all reflected electrons to the target. For example, if the energy of the incident electrons is 4 MeV, the energy conversion coefficient of the accelerated beam to Bremsstrahlung in the forward direction is KX (4 MeV) ≈ 6%. Let us assume (for the purpose of simplicity) that all reflected electrons have the half-energy (i.e. 2 MeV) and are returned normal to the target. For 2 MeV electrons KX ≈ 2,5% and since the part of the power of the reflected beam is about 16%, by multiplying these numbers we will have ΔKX = 0,16×0,025=0,004 or 0,4% of additional Bremsstrahlung power which accounts for a 7-8% increase of the power of the X-ray radiation generated by the initial electron beam. Absence of the absorber for the electrons that pass through the target allows increase the useful X-radiation power by another 15%, i.e. the sum effectiveness of the X-ray target will be higher on 20% approximately.

Summarizing it can be concluded that usage of the IFFSM for any kind of accelerators with extraction of electron beam into atmosphere provides practically non-divergent electron beam and allows to decrease the installations sizes (due to geometry factors), lessen beam power losses (due to angles between the electron trajectories and a foil plane to be close to normal) and built the installations capable for two-side irradiation of materials by one accelerator and during one pass of the material.

For installations generating Bremsstrahlung, as it is shown, the IFFSM allows to increase X-ray release by using power of reflected electrons and absence of X-ray radiation losses in an absorbing layer [6,7].

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