X-RAY RADIATION INTENSITY INCREASE BY MEANS OF A DISCRETE TARGETS IN A MAGNETIC FIELD

P. Alferov, B. Bogdanovitch, A. Nesterovitch, Yu. Pomazan, S. Stepanov,
MEPhI, Moscow, Russia

The electromagnetic continious x-ray radiation (or bremsstrahlung) has found wide application in various areas of science and engineering first of all due to it's greatest penetrating ability in comparison with other types of radiations. Electron linacs are usually used as a source of particles. For increase of a bremsstrahlung output it is necessary to raise thickness of a target, thus a radiation divergence cone angle can make tens of degrees, so intensity of bremsstrahlung is decreased. For various nuclear numbers of a target substance and electron energies there is the so-called optimum thickness of a target, with which the bremsstrahlung output reaches the maximum. However, when using a target with optimum thickness not all electron energy is absorbed in a target material.

In the report involved one of ways of bremsstrahlung intensity increase is described. In this method the electron flow is transported from the linac output in such a manner that, passing a sequence of "thin" targets (futher we shall call its "foils") which thickness is essentially (on the order) less, than optimum one, in aggregate forming a "thick" target, which thickness can exceed optimum and even radiating thickness, is "cooled" on each site between the next "thin" foils. Thus, "thin" foils can have such displacement and form, that the radiation from previous foils passes by next one in the same direction. In contrast to a case of the solid "thick" target with equivalent combined together thin foils length, the angular disorder on each of sites of a trajectory is not summarized, but decreases, or, at least, remains as previous, if the factor of beam emittance increase in each foil is equal to factor of beam emittance reduction (equivalent to increase of a beam cross size in " cooling system ") on a site of transportation up to the following foil.

In the elementary case this method can be realized in a system with an adiabatically decreasing magnetic field formed by a sequence of solenoids. In Fig.1 the experimental facility scheme for checking of the offered variant of bremsstrahlung flow with small angular divergence formation is shown. The electron beam from the linac passes through a foils sequence F1, F2, F3..., each of which is located on a site in a central zone of the appropriate solenoids S1, S2, S3..., where the magnetic force lines direction coincides with a direction of a longitudinal axis of system.

The accelerator, designed for acceleration of kA electron currents in beams of tubular shape [1] can be used as linac with the superconducting solenoids focusing in operating variant of practical realization .

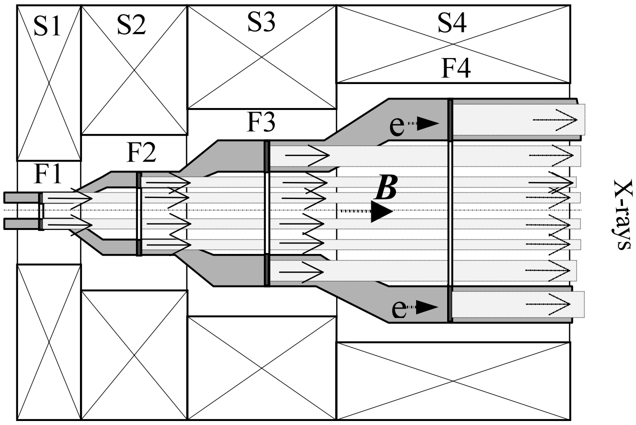

Figure1. The scheme of an experimental facility fo bremsstrahlung flow with small angular divergence formation by means of a solenoids sequence.

With the analysis of processes occurring with an electron beam passage in the facility, we shall use the following characteristics: *We* - an electron energy, $\omega \; e\cdot B/m_0\cdot\gamma$ - cyclotron frequency, (e , m_0 , $\beta \;\; V_{//} / c$, $\gamma \; W_e/m_0\cdot c^2$ - an accordingly are charge, mass, relative speed and dimensionless electron energy , B - is a magnetic field induction), $r \;\; V_{\perp}/\omega$ - is cyclotron radius ($V_{\perp}$ - is transverse electron velocity), $r' \;\; V_{\perp}/V_{//}$ - is an angle of an electron trajectory inclination to an axis ($V_{//}$ - is longitudinal electron velocity). First of all, we shall define conditions of an adiabatic magnetic field change . In our case it means, that the time of one electron cyclotron revolution in a magnetic field T_c should be much less, than time of electron passing through a section of length L with the given magnetic field value B: $T_c \;/\; t \ll 1$, or:

$$\frac{2\cdot\pi\cdot\gamma\cdot m_0\cdot V_{II}}{e\cdot B\cdot L} << 1 \qquad (1)$$

From this ratio it is clear, that with the reduction of a magnetic field B and small losses of electron energy in a foil, a section length grows, that imposes restrictions on the minimal magnetic field value, which can be used in facility, related to the allowable longitudinal sizes. For example, with We = 5 MeV ($\gamma\sim$ 10) and a foil thickness equal to 0,1 mm electron energy losses in foil will be approximately equal to 45 keV (for *Al*), i.e. T_c and t practically do not change. Then, by accepting t = $20\cdot T_c$ and length of the latter, most extended section equal to 4m, we get value B ~ 0,5 T. It is obvious, that use of smaller values of B is inexpedient from constructive reasons.

Let's proceed to consideration of questions connected to an electron beam "cooling", i.e. with transverse electron velocity (r') reduction. On a site between two next foils an electrons consistently pass the area of a homogeneous magnetic field, then area of a magnetic field recession and, further, again the site with a homogeneous magnetic field. In each cross section the magnetic field is constant (does not depend on radius and azimuth). Using an adiabatic invariant method [2], it is possible to obtain the following parities:

$$\pi \cdot B \cdot r^2 = const \quad \text{and} \qquad (2)$$

$$\omega \cdot R \cdot (2 \cdot r - R) = const, \qquad (3)$$

where radius R characterizes an electron position relative to an system axis of symmetry.

From Eq. (2) it is visible, that cyclotron radius $r \sim B^{-1/2}$, at the same time cyclotron frequency $\omega \sim B$, and from the formula (3) follows, that:

$$a_2 = a_1 \cdot \sqrt{B_1 / B_2}, \quad R_2 = R_1 \cdot \sqrt{B_1 / B_2}, \qquad (4)$$

where a - is an electron trajectory axis displacement relatively a system axis of symmetry.

Using these ratios one can estimate transverse beam sizes.

Taking into account that $V_\perp = \omega \cdot r$, after simple transformations an expression for electron beam angular divergence reduction after passage of space between foils (process, named above as " cooling ") is obtained:

$$r_2' = \sqrt{\frac{B_2}{B_1}} \cdot \frac{r_1'}{\sqrt{1 + r_1'^2 \cdot (1 - B_2 / B_1)}} \qquad (5)$$

The value of expression in a denominator of the Eq. (5) is essential more than 1 only with large (more than 0,5) values of r' and small (less than 0,5) values of the ratio B_2/B_1. Therefore in the first approximation with an accuracy up to some percents it is possible to suppose, that $r' \sim \sqrt{B}$.

For an estimation of electron scattering in foils we shall use the following expression for a root-mean-square scattering angle in a plane of a trajectory [3]:

$$\varphi_{scatt} = \frac{z \cdot E_S}{W_e \cdot \beta^2} \cdot \sqrt{\frac{t}{2 \cdot X_0}} \qquad (6)$$

where: $E_S = \sqrt{4 \cdot \pi \cdot 137} \cdot m_0 \cdot c^2$, and

$$\frac{1}{X_0} = \frac{4 \cdot z \cdot (z+1) \cdot r_e^2 \cdot N_0}{137 \cdot A} \ln\left(\frac{183}{z^{1/3}}\right) \qquad (7)$$

Value X_0 which is taking into account properties of a target substance , is named as radiating length.

As electrons get on a foil at an angle, different from 90^0, complete root-mean-square angular disorder in a beam φ_e after passing of a foil we shall define as follows:

$$\varphi_e = \sqrt{r'^2 + \varphi_{scatt}^2}, \qquad (8)$$

where: r' - is an angular disorder in a beam on a foil inlet. As the electron flow intensity is proportional to $(r')^{-2}$, relative increase of it in comparison with a "thick" target can be defined accordingly to the formula:

$$I_{e\,rel} = \varphi_{th}^2 / \varphi_e^2, \qquad (9)$$

where φ_{th} - is the scattering angle appropriate to an equivalent "thick" target with $t_{th} = N_F \cdot t$ (Eq. (6)), φ_e - is defined from the Eq. (8).

While passing a target an electron at each individual act of interaction with atoms of substance produces a bremsstrahlung flow with minimal divergence $\varphi_R \sim 1 / \gamma$ relative to an electron movement direction. Therefore maximum value φ_R in root-mean-square approximation can be estimated as:

$$\varphi_R = \sqrt{\varphi_e^2 + 1/4\gamma^2} \qquad (10)$$

In Fig.2 the calculated dependences φ_R upon used foils thickness t_F are given with various values of a magnetic field recession ($n_B = B_1/B_2$), which supposed identical in all sites. There angular divergence of a bremsstrahlung flow for an electron beam, past "thick" target of equivalent thickness, is shown by a dotted line. The results are given for a foil number N_F equal 4 and 7.

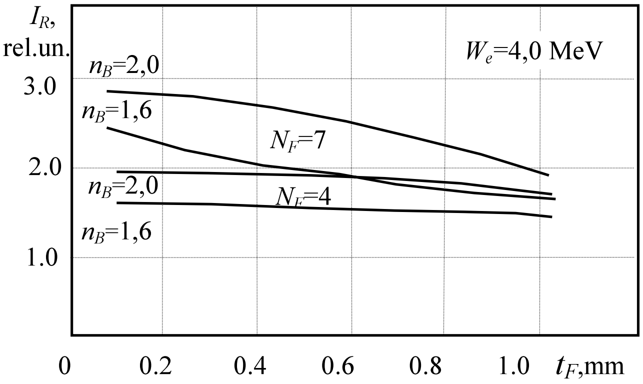

Figure3. Calculated dependences of a relative bremsstrahlung flow intensity increase I_R upon foil thickness t_F with various n_B and N_F values, - - - - "thick" target.

The relative increase of bremsstrahlung flow intensity $I_R = \varphi_{Rth}^2 / \varphi_R^2$ with use of "thin" foils is shown in Fig.3.

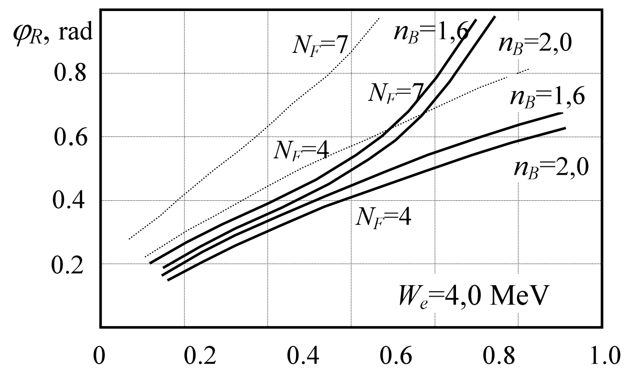

Figure 2. Calculated dependences of a bremsstrahlung flow divergence φ_R upon foil thickness t_F with various n_B and N_F values,
- - - - "thick" target.

The analysis carried out above shows, that all "angular" characteristics of a beam and radiation do not depend on absolute value of a magnetic field induction *B*. At the same time, beam radius *R* and the length of sections directly depend on value *B*. It is possible to determine length of sections, proceeding from an adiabatic magnetic field change conditions (1), mentioned above, accordingly to the following formula:

$$d=\frac{2\cdot\pi\cdot N_C\cdot\beta\cdot c\cdot m\cdot\gamma}{e\cdot B} \text{ or } d=0{,}0107\cdot N_C\cdot\beta\cdot\gamma/B \quad (11)$$

where N_C - is the cyclotron revolutions number made by electron in a length *d* of section.

As it was already mentioned above, with value B<0,25T length of sections becomes more than 8 m.Total length of the device will be defined by number of foils used N_F, which is equal to number of sites with a constant magnetic field, by value of a magnetic field n_B recession and by a magnetic field on the first site value B_1.

Taking into account that the device length can be limited by value of the order 10 m (a high current linac can have approximately the same length), on the basis of the accounts carried out it is possible to offer some possible variants of facility performance. In Table 1 the calculated parameters of some variants of the offered device are given under conditions N_C = 20, γ = 8, β ~ 1. The magnetic field on the first site value B_1, magnetic field recession parameter n_B, number of foils N_F, total system length *L*, divergence φ_R (half of total angle), relative bremsstrahlung flow intensity increase I_R are specified. Foil thickness in all variants is equal to 0,5 mm, a foil material is *Al*.

Table 1.

Var. No.	B_1, T	N_F	n_B	φ_R, rad	I_R	*L*, m
1	7	7	1,6	0,49	2,29	7,36
2	7	5	2,0	0,39	2,25	5,93
3	10	7	1,8	0,47	2,54	8,8
4	10	4	3,0	0,33	2,34	5,59
5	15	7	2,0	0,45	2,73	9,74
6	15	4	4,0	0,31	2,54	7,85

The calculated changes of a magnetic field induction *B* and external electron beam radius *R* along the device length *L* for the variants are given in Table 1, are shown in Fig.4.

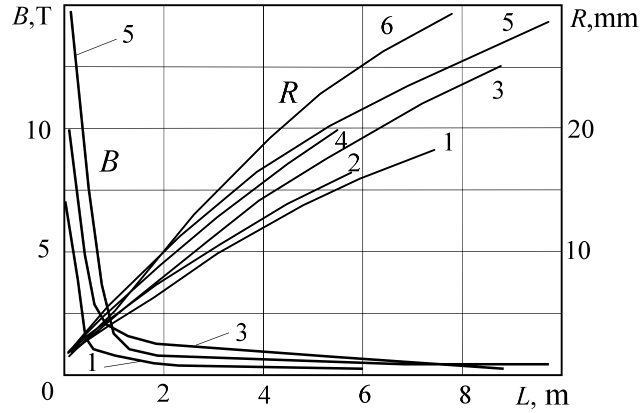

Figure 4. The calculated changes of a magnetic field induction *B* and external electron beam radius *R* upon the device length *L* for the variants are given in Table 1.

The results obtained have preliminary character and assume the subsequent correction from the point of view of detail optimization criteria development (accordingly to efficiency, angular divergence, length etc.). However it is possible to make a conclusion about an opportunity and prospects of the offered technical decision for the defectoscopy and large-sized loads customs control tasks.

REFERENCES

1. Sarantcev V., Perelstein E. Collective acceleration of ions by means of electron rings (in Russian). M.: Atomizdat, 1979.
2. Kirstein P. at al. Formation of electron beams (in Russian). M.: Mir, 1970.
3. Perkins D. Introduction to high energy physics (in Russian). M.: Mir, 1975.