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BREMSSTRAHLUNG PRODUCTION BY MICROSECOND E-BEAM FROM THIN FOIL IN A MIRROR TRAP

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Abstract.Experiments on a microsecond E-beam (1 MV, 50 kA, 60 kJ) interaction with a bremsstrahlung converter are described. A thin foil placed between strong magnetic mirrors is used as a target. Multiple passage of the electrons through the thin foil increase bremsstrahlung yield in the low-energy (<50 keV) range of spectrum. Testing of the suggested converter has been carried out. The effect of oscillating electrons on the microsecond diode operation is discussed. It is found that the target with thickness equal to 0.05 of the mean range absorbes the beam practically totally. The time-resolved measurements of X-ray emission uniformity are also presented.

Introduction.

Bremsstrahlung sources of different types for various applications have been developed recently. In most of these applications the important parameter is the energy deposition in an irradiated sample. The absorbed energy is determined by the fluence and absorption coefficient of photons which strongly depend on the photon energy. Thus, bremsstrahlung converters with enchanced yield in the soft range of spectrum have a greate importance.

In a conventional converter a high-atomic-number material with thickness about mean electron range is used. As a result the self-absorption reduce essentially bremsstrahlung yield in the low-energy part of spectrum. For materials with $Z\sim70$ (W,Ta) the low-energy edge is about 50 keV.

To increase the yield in the soft part of spectrum the advanced converters [1], in which electrons make multiple passes through a thin foil, are used. 'Multiple passes scheme' is realized, for instance, for the drift motion of electrons in the magnetic field of linear current [2]. Another approach is to use the scheme, in which the beam electrons oscillate between an accelerator cathode and a virtual cathode [3,4]. This last scheme can be applied effectively only for a short beam duration (<100 ns), because for the high-power microsecond E-beam its space charge is neutralized in a short time by the ions generated on the accelerator anode foil and on the target foil [5].

In this paper the possibility of the electron beam trapping between strong magnetic mirrors to realize multiple passes through a thin target foil is studied. An electron beam is injected into a trap through the entrance magnetic mirror. Between the mirrors a thin scattering foil is installed, which is used as a bremsstrahlung converter. After the first pass through the foil a part of the beam electrons obtains a pitch-angle large enough to be reflected from the exit mirror. By changing the foil thickness the main part of the beam electrons can be catched in the trap even for the foil thickness essentially less than the mean range of the beam electrons. The advantages of such an approach are the following.

a) There is no feedback effect of reflected (oscillating) electrons on the accelerator diode operation in contrast with the system of virtual cathode.

b) It becomes possible to use a microsecond beam, because the beam space-charge neutralization and destruction of the virtual cathode do not affect the scheme realization.

Experimental device and diagnostics.

The experiments have been performed on the U-1 device [6]. The experimental configuration is shown schematically in Fig.1. The electron beam (0.8 MV, 60 kA, 3 μs, 60 kJ) is generated in a vacuum diode with a quasiplanar 21 cm diameter graphite cathode. The cathode-anode gap is 5-8 cm. After passing through a thin anode foil 7 (aluminized mylar 10 μm) the beam is adiabatically compressed in the mirror magnetic field and injected into a magnetic trap. Magnetic field increases from 0.5 T in the diode to 10 T in the mirror. The distance between the mirrors 2 and 3 is 40 cm and the mirror ratio $B_{max}/B_{min} = 11$. If the target foil 8 is not installed, the beam passes through the second mirror to the collector 10 without loss. Al, Ti and Ta foils of various thickness have been used as a bremsstrahlung converter. The target foil position can be varied as shown in Fig.1.

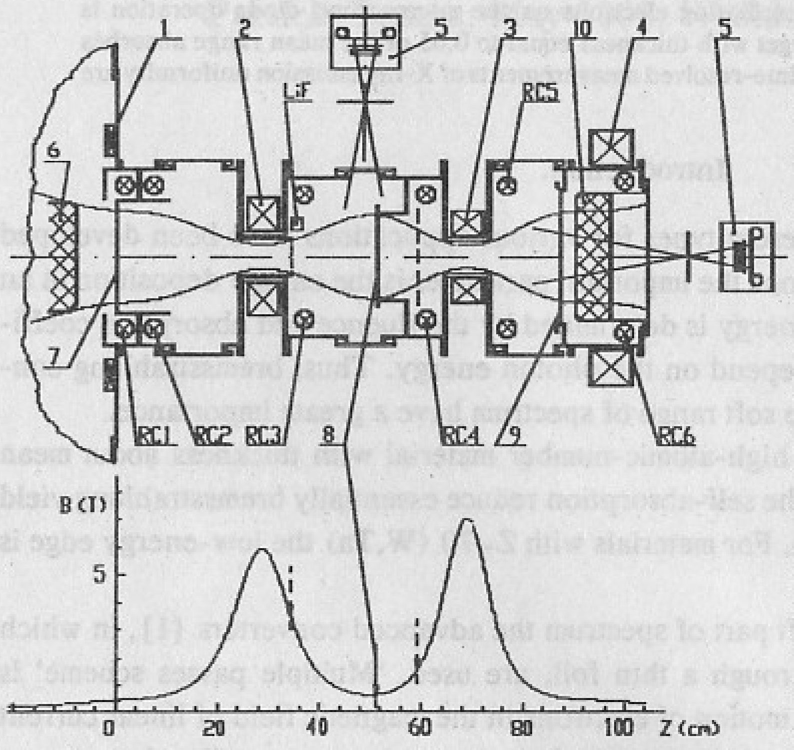

Fig.1 Schematic of the experimental device: 1-4 - magnetic coils, 5- x-ray image converter, 6 - cathode, 7- anode foil, 8- target foil, 9-collector foil, 10-collector, "LiF"-TLD position. Bottom - magnetic field along the axis.

The beam current at the entrance and on the collector, as well as the net current have been measured by Rogowski coils RC1-RC6. To measure the size of the emitting region and the radiation uniformity over the target surface we have used an x-ray image converter on the basis of a microchannel plate. Time and spatial resolution of this system is 0.3 μs and 0.5 cm respectively. Hard x-rays are monitored by a PIN diode. Several LiF thermoluminescent dosimeters (TLD) measured the dose inside the vacuum chamber at a 15 cm distance from the target. To determine the bremsstrahlung spectrum we have measured the dose behind the different filters.

Experimental results and discussion.

1. Beam absorption in the target.

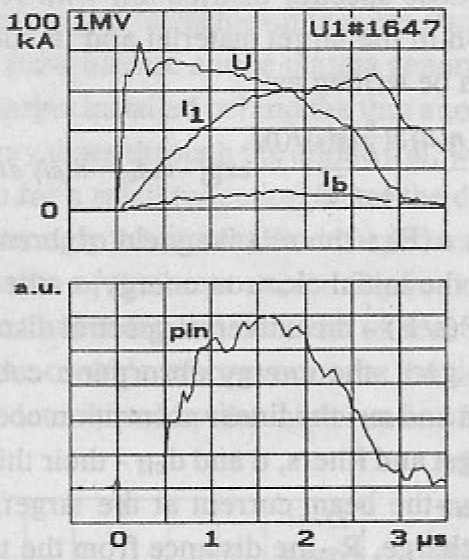

Fig.2 Diode voltage, currents and PIN - diode signals. Target - 30 μm Ta.

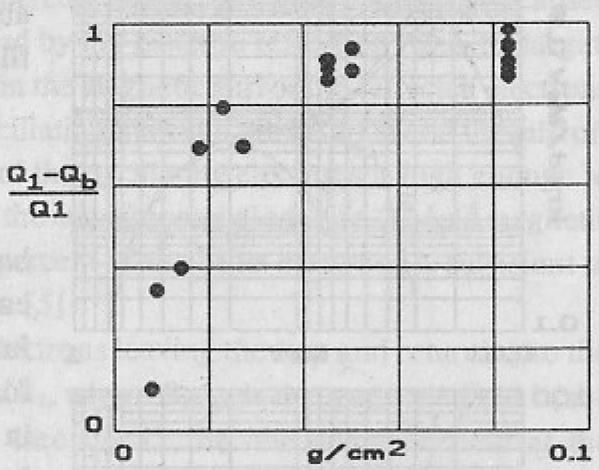

Fig.3 Efficiency of the beam absorption in the target versus the target thickness (Al, Ti, Ta)

Typical signals illustrating the efficiency of the beam capture in the target are shown in Fig.2. The diode voltage U is up to 0.8 MV and injected beam current I_1 rises up to 60 kA. The pulse duration (3 μs) is determined by the diode gap (6 cm). The total energy of the beam $Q_1 = \int UI_1\, dt$ is 60 kJ. The beam current at the exit collector I_b (measured by RC6) changes depending on the thickness of the target foil. The difference between I_1 and I_b is the current of electrons sticked in the target. Efficiency of the beam capture in the target versus the target thickness (g/cm^2) is shown in Fig.3. The almost complete beam capture (>80%) occurs at the thickness > 0.02 g/cm^2, that is about 0.05 of the beam electrons mean range.

Typical converter images for the moment of maximum x-ray intensity (2μs) are shown in Fig.4. The diameter of the emitting region, measured by image converter, is equal to expected that of the beam at the target according to the magnetic lines of force. This diameter is 14 cm for target positioned in the middle of the trap (mirror ratio M=11) and 10 cm for M=5. X-ray emission during the pulse is uniform over the target surface.

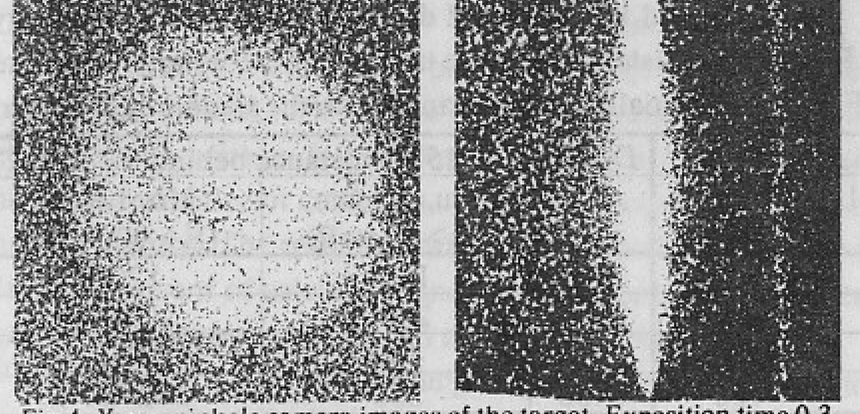

Fig.4 X-ray pinhole camera images of the target. Exposition time 0.3 μs. The right picture is made through the side window and the weak strip at the right corresponds to x-ray reflection from the side surface of the window.

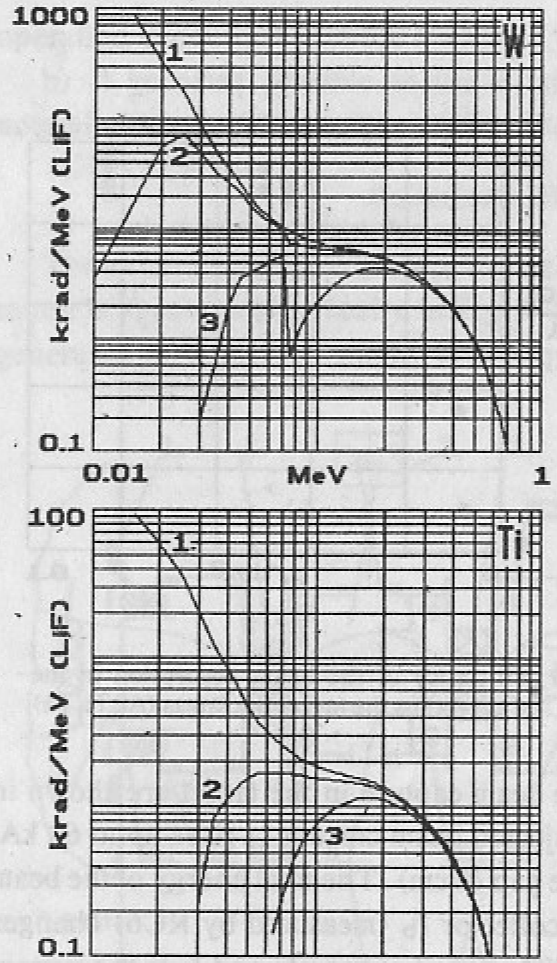

Fig.5 The spectral dose distribution. Top-tungsten target. Thickness: 1- 0 μm , 2- 15 μm, 3- 150 μm. Bottom- 100 μm tifanium target. 1-without filter, 2- 0.5 mm Cu filter, 3- 1 mm Mo filter.

2. Bremsstrahlung spectrum.

The dose spectral distribution with regard to absorption in the target material and in additional filters can be written as:

$$D_\varepsilon=\int \frac{n(E)F(\frac{\varepsilon}{E})g(\varepsilon)I(t)f}{4\pi R^2 e}\exp(-md_{eff}-m_f d)\ dt$$

where n(E) - the relative yield of bremsstrahlung, E - the initial electron energy, ε -the photon energy, F(ε/E) - the universal spectral distribution function, g(ε) -the energy absorption coefficient for LiF, m and m_f -the linear absorption coefficient in the target and filters, d and d_{eff} - their thickness, I(t)=I_1-I_b -the beam current at the target, e -the electron charge, R -the distance from the target to the point of measurment and f -the geometry factor equal to 0.75 for the chosen position of TLD.

The calculated spectral doses for different effective target thickness d_{eff} and for various filters are shown in Fig.5. The multiple electron passes through a thin target essentially increase the yield of soft x-rays in the range of 10-50 keV.

The calculated and measured doses behind the different filters are presented in the table below. The measured and calculated doses for the 100 μm Ti converter foil are practically the same, and the measured dose of soft x-rays with energy lower than 50 keV is about 1 kR at a 15 cm distance from the target. For the W target the dose in soft region is about 4 kR (LiF) and is essentially greater than that for the standard converter.

target			Dose (R) at 15 cm distance behind the filters		
	material	thickness, μm	-	Cu, 0.5 mm (E > 40 кэВ)	Mo, 1 mm (E > 90 кэВ)
Calculation (Q_1=60 kJ)	W	150	1700	1500	1200
	W	15	3900	2000	1500
	Ti	100	1700	400	300
Experiment	Ti	100	1400	350	290

3. Converter effect on the diode operation.

One of the questions for suggested converter is about the influence of the reflected electrons on the microsecond diode operation. It is well known that high-atomic-number materials used

as an accelerator anode or installed in the magnetic mirror behind the anode foil change essentially the diode operation. Under such conditions the diode begins to operate in bipolar mode earlier and the achievable pulse duration decreases [7,8,5]. These changes are caused both by more intense anode plasma generation and by the electron reflection from the target. For the target installed behind the thin anode foil in the magnetic mirror the reflected electrons pass many times through the anode foil, while oscillating between the cathode and the mirror. So, even for a small reflection factor the density of the oscillating electrons is high enough to reduce strongly the bipolar diode impedance. For the microsecond diode and 20-fold magnetic compression of the beam even reflection of few percent of the beam electrons is sufficient to decrease the beam pulse duration of several times [5].

For the considered converter the fraction of electrons leaving the trap and returning to the diode is determined by the mirror ratio M=B_{max}/B_t, where B_{max} is the magnetic field in the mirror 2 (see Fig.1), B_t -the magnetic field at the target. If this mirror ratio is large enough, the target will not strongly affect the diode operation.

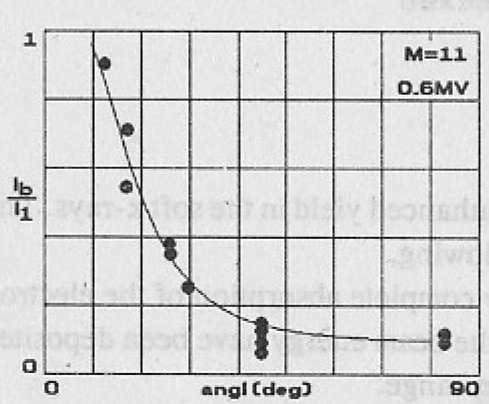

Fig.6 Fraction of the injected beam current passed to the collector versus the target r.m.s. scattering angle. Points - measured data, line - calculated data after one pass through the target foil.

Experimental estimation of the electron current into the diode can be made as following. The electron current to the exit collector, measured by the coil RC6, is the sum of two values. The first value is the fraction of primary beam not trapped after passing through the target foil due to their pitch-angles θ is less then $\theta_M=arcsin\frac{1}{\sqrt{M}}$. The second one is the current of trapped electrons which obtain the pitch-angles $\theta < \theta_M$ due to scattering in the target foil and leave the trap. Given the magnetic field in the mirrors is the same and the trapped electrons make many passes through the target, this second part of collector current is equal to the current of electrons leaving to the diode. The part of the beam directly passed to the collector can be calculated knowning the voltage, foil thickness and mirror ratio. Comparing the calculated value with the measured collector current I_b, one can estimate the current of electrons leaving the trap as their difference. The result of such acomparison for the mirror ratio M=11 is shown in Fig.6. Good agreement of calculated and measured currents indicates that for this mirror ratio the number of electrons returning to the diode is small.

To increase the bremsstrahlung brightness it is necessary to increase the current density on the target. It may be achieved by installing the target in the maximum permissible magnetic field. For this purpose the experiments have been performed in which the target position was varied and the mirror ratio changed from M=11 to M=2. The experiments showed that for M>6 the diode operates without any features and its impedance and pulse duration are the same as for the case without target. For the smaller mirror ratio the diode impedance decrease faster and pulse duration became shorter in a factor of 1.5 for the mirror ratio M=5 and in a factor of 3 for M=2 (pulse duration for the last case is less than 1 μs, see Fig.7). Thus, efficient operation of the suggested converter for a long pulse beam can be achieved with M>6.

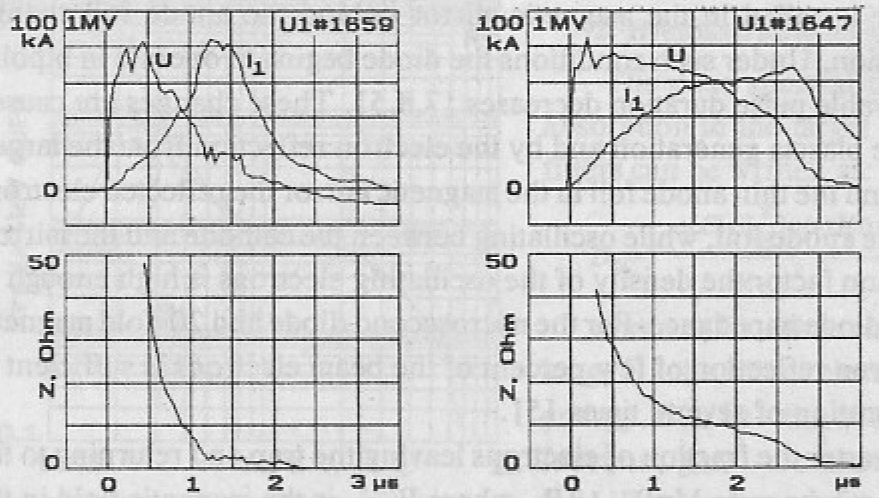

Fig.7 Effect of target position on the diode operation. At the left - B_{max}/B_t=2, at the right - B_{max}/B_t=8.

Summary.

We have described a bremsstrahlung converter with enhanced yield in the soft x-rays. The main results of the experiments can be summarize as following.

1. The conditions have been found of the practically complete absorption of the electron beam in a thin target. In our experiments, up to 80% of the beam energy have been deposited in the foil with thickness of 0.05 the beam electron mean range.

2. For the 100 μm Ti target and injected beam energy content 60 kJ the measured dose (LiF) in soft x-rays (<50 keV) at a 15 cm distance from the target is 1 kR and total irradiated surface is 1000 cm^2. For the 10 μm W target and 180 kJ E-beam [9] this dose will be 15 kR per pulse.

3. The bremsstrahlung intensity over the target surface is uniform. The emitting region diameter is determined by the ratio of the magnetic field in the mirror to that on the target. The minimum achievable emitting diameter is limited by the effect of the reflected electrons on the diode operation.

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Bremsstrahlung Production by Microsecond E-Beam From Thin Foil in a Mirror Trap

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П.И. Мельников, М.А. Щеглов, С.Г. Воропаев

Генерация рентгеновского тормозного излучения с тонкой мишени микросекундным РЭП, захваченным в пробкотрон

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