TRAVELLING WAVE DEFLECTOR FOR FREE ELECTRON LASER

***A.A. Anisimov, V.I. Kaminskij, M.V. Lalayan, N.P. Sobenin, A.A. Zavadtsev*[1]**
Moscow Physics Engineering Institute (State University);
[1]JSC "Nano-Invest, Ltd"
E-mail: sobenin@mail.ru

For the measuring system of electron bunch length and emittance at free electron laser there were examined both the known configuration in the form of disc loaded waveguide with two holes for the wave polarization plane stabilization and the new versions of the deflector: with peripheral recesses (two grooves in the cowling) and with the oval aperture.

PACS 29.17.+w, 29.27.Eg

1. INTRODUCTION

The linear electron accelerators with the superconductive accelerating structures are base installations of contemporary free electron lasers (FEL). The radiation brightness of these lasers is very large because of the high average power of the accelerated beam, which generates coherent radiation. Radiation wavelength at FEL can be essentially adjusted; in particular, FEL can work in the X-ray range. Nowadays intensive development of free electron laser of X-ray range (X-ray Free Electron Laser, X-FEL) is conducted at scientific center DESY (Germany) with the participation of a number of countries, including Russia. Maximum beam energy will be 20 GeV, the radiation wavelength 0.1 nm [1].

Installation must be equipped with the metrological equipment, which ensures quality control of the accelerated beam. Accelerating structure with traveling wave and transverse deflection field is considered as tool for bunch length measuring, and also as additional means with the analysis of free electron laser phase space at X-FEL project [1]. The prototype of this structure can be disc loaded waveguide operating on E_{01} wave type with two diametrically located holes in diaphragms for the stabilization of wave polarization plane [2,3]. Usually deflectors with travelling wave are designed for operation at *S*-band with 2π/3 mode and wave relative phase velocity $\beta_{ph}=v_{ph}/c=1$.

2. ELECTRODYNAMIC CHARACTERISTICS

Table 1 includes requirements for three deflectors of the X-FEL project. Main electrodynamic characteristics, which are the basis of the selection of the deflector type, include the following parameters: linear transverse shunt resistance ($r_{sh\perp}$), the relative group velocity (β_{gr}), the electric field maximal gradient on the surface ($E_{S\,max}$), the microwave power attenuation factor (α). Important parameter is the frequency separation of main and neighbor oscillation modes. Table 2 includes data of three frequency differences $\Delta f_i=f_0-f_i$, (i = 1,2,3), which are of interest at structure study. Here frequencies f_0 and f_3 are oscillation frequencies at 2π/3 mode and π mode for working polarization. Frequencies f_1 and f_2 are oscillation frequencies at 2π/3 mode and π mode respectively for other polarization. In all calculations f_0 =3000 MHz.

For obtaining the assigned deflecting voltage $V_\perp$ at any of three sections with the assigned adjusting lengths and the input power indicated it is necessary to fulfill of condition:

$$E_{0\perp}\lambda/\sqrt{P}>(220\ldots240),\ \Omega^{1/2}.$$

Values $|\beta_{gr}|$>0.016 ensure the section required filling time with microwave power τ. For the exception of excitation of mode with nonworking polarization at operating frequency f_0 it is desirable to have frequency separation Δf_2 > 15 MHz.

In the process of deflector optimum version selection, first of all, it is necessary to calculate dispersion characteristics of the wave E_{11} with two polarizations. The linear transverse shunt resistance is the important parameter of deflectors. It is calculated by the formula [4]:

$$r_{sh}=\frac{\left(\int_0^l\left|E_z(z)_{x=a}\right|dz\right)^2}{(ka)^2}\frac{1}{Pl}=\frac{V_\perp^2}{Pl}. \quad (1)$$

Here $x=a$ is distance from the axis, at which distribution of electric field longitudinal component along the coordinate $E_z(z)$ was calculated; $P=\omega U/Q$, where U – energy, stored up for the length l of the designed section; $k=2\pi/\lambda$, where λ – oscillation wavelength.

Transverse deflecting voltage $V_\perp$ is connected with the transverse deflecting electric field $E_{0\perp}$ with deflector length l as follows:

$$V_\perp=\int_0^l E_{0\perp}e^{-\alpha z}dz=\frac{E_{0\perp}\left(1-e^{-\alpha l}\right)}{\alpha}. \quad (2)$$

In calculations of deflector with travelling wave characteristics it is used normalized transverse field gradient [5]:

$$\frac{E_{0\perp}\lambda}{\sqrt{P}}=\sqrt{\frac{2\pi\lambda r_{sh.\perp}}{\beta_{gr}Q}}. \quad (3)$$

Table 1.

X-FEL deflector characteristics

Characteristics	Deflector type		
	TDS1	TDS2	TDS3
Beam energy W, MeV	130	500	2000
Deflecting voltage $V_\perp$, MV	1.7	14	27
Maximum base length l, mm	0.7	1.6	3.6
Filling time with microwave power τ, ns	<120	<320	<320
Input power P, MW	2.5	26.3	2×20.7

PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2010. № 2.
Series: Nuclear Physics Investigations (53), p.56-59.

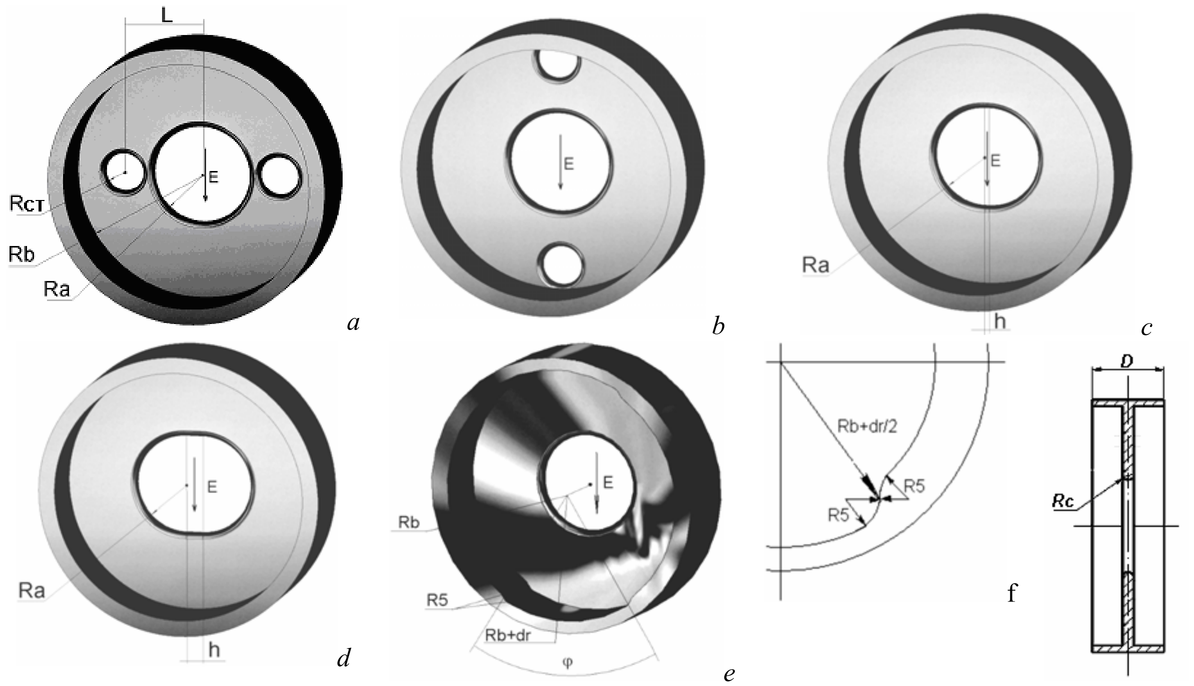
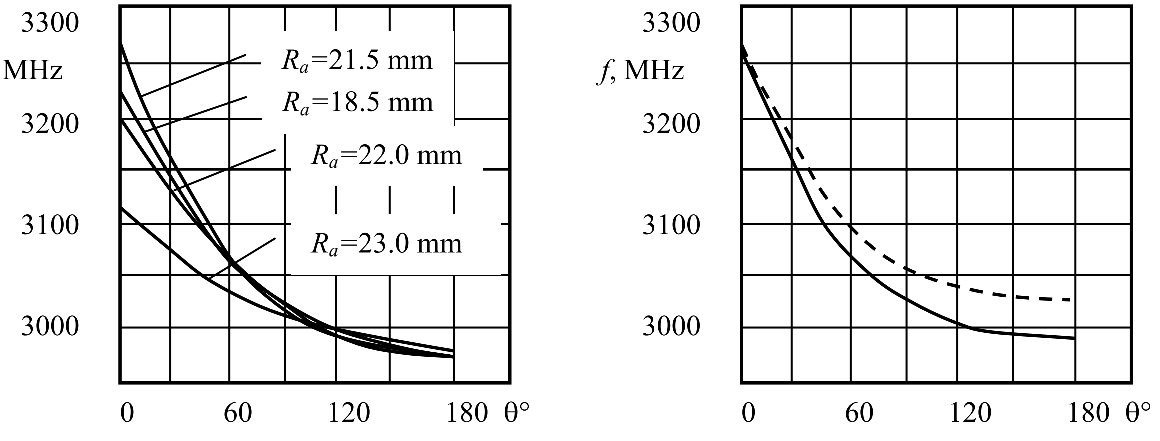


Fig.1. Deflecting structure variants

Researched structures are shown in Fig.1. Structure characteristics were calculated and compared for selection of optimum profile of deflector section. Variants of deflector structure are: a, b – with two stabilization holes; c, d – with the oval aperture, e –with two peripheral recesses; f – rounding of the peripheral recesses and the longitudinal cutting section of cells. Designation шn the Fig.1 are: R_b – radius of cell; R_a – radius of aperture; D=33.31 mm – period of structure; $R_c = t/2$ – radius of rounding of aperture hole in the diaphragm (t = 5.25 mm – thickness of diaphragm); R_{st} – radius of the stabilization holes, L – radial position of stabilization hole axes; h – distance between centers of two semicircles with a radius of R_a in the oval aperture; dr – increase in the radius R_b on the angular dimension φ. Fig.1,f is depicted fragment of structure drawing with rounding of the peripheral recesses with indication of lines of sharp boundary rounding, and also longitudinal cutting of cells. Vector E shown in pictures in Fig.1 is the direction of deflecting transverse component of electric field E_{11} for the working polarization.

3. DEFLECTOR WITH STABILIZATION HOLES

It is known use of round disc loaded waveguides with two circular holes for polarization plane stabilization of wave E_{11} as the deflector (see Fig.1,a). It is important to study influence of hole size in diaphragm R_a, radius size R_{st} and position L of stabilization holes to deflector electrodynamic characteristics. Dispersion curves at different values of hole radius in diaphragm R_a are represented in Fig.2. Structure operates on the wave E_{11} with the stabilization holes of radius R_{st}=8.5 mm, located at distance from cell axis of $L=R_a$+13.5 mm. This location of stabilization holes is accepted in the works [2,3]. Character of dispersion curved on the wave E_{11} changes depending on hole radius in diaphragm. With R_a=23.0 mm the passage from negative dispersion to positive one takes place.



a *b*

Fig.2. Dispersion curves of structure with R_{st} = 8.5 mm and $L=R_a$+13.5 mm at various R_a (a) and dispersion curves of two polarizations at R_a=22 mm (б); θ – oscillation mode

Stabilization holes can be positioned near cowling ($L=R_b-10.5$ mm). Comparison of characteristics for two cases of positioning of stabilization holes is given in Table 2 (versions a, b). It must be noted, that with $L=R_b-10.5$ mm the deflection field of the wave E_{11} is located in the plane, passing through the axes of the stabilization holes. Dispersion curves of working polarization with different radii of hole in the diaphragm R_a are given in Fig.2,a. Solid line in Fig.2,b depicts dispersion curve for the working polarization, and broken line – for the perpendicular polarization.

4. DEFLECTOR WITH OVAL APERTURE

On the basis of structure with the oval aperture (see Fig.1,c,d) it is possible the creation of deflectors with the necessary characteristics with two values of distance h between the centers of hole rounding radii in the diaphragm. Corresponding calculation data for the structure versions are shown in Table 2 (c,d). With h near 1.7 and 7.5 mm of the value of group velocity and given gradient of transverse component of electric field correspond to presented requirements.

5. DEFLECTOR WITH PERIPHERAL RECESSES

For the structures with two peripheral recesses (see Fig.1,e) it was researched influence of aperture angle of the turning φ and its depth dr, first of all, to the separation of frequencies. Structure with the hole in diaphragm of radius R_a=21.5 mm was examined. Taking into account requirements for the characteristics of deflector and production technology of structure with the peripheral recesses, it is preferable to select depth of peripheral recesses of small (dr=1 mm) and the angle of its solution of φ = 65°. Corresponding characteristics for this structure are presented in Table 2, variant e.

Table 2.

Geometrical and electrodynamical parameters of structure various variants

Parameter	Structure variants, see Fig.1				
	a	b	c	d	e
L, mm	35.0	45.6	–	–	–
R_{st}, mm	8.5	8.5	–	–	–
h, mm	–	–	1.7	7.5	-
φ, degree	–	–	-	-	65
dr, mm	–	–	-	-	1
R_a, mm	21.5	22.0	20.5	21.5	21.5
R_b, mm	55.38	55.04	55.49	53.39	55.03
α, 1/m	0.153	0.150	0.148	0.153	0.147
β_{gr}	–0.017	–0.018	–0.017	0.018	–0.017
$R_{sh\perp}$, MΩ/m	19.17	18.60	21.07	18.00	19.84
Q	11804	11934	12190	11650	12272
Δf_1, MHz	–23	–20	–30	–169	–27
Δf_2, MHz	–12	–13	–27	–175	–17
Δf_3, MHz	11	12	12	–17	11
$E_{0\perp}\lambda/\sqrt{P}$, $\Omega^{1/2}$	242	235	252	232	242

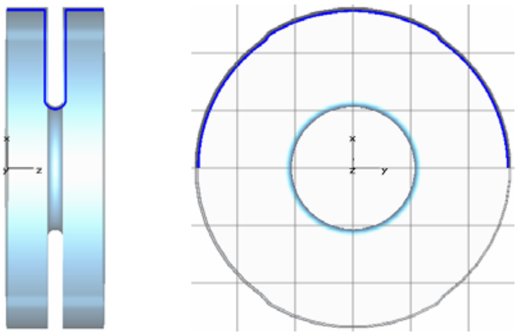
Values of sensitivity functions (MHz/mm) for the structure type e from Table 2 are given below. These functions are the shift of oscillation frequency at 2π/3 mode with a change in structure dimensions. In the last column sensitivity function to the aperture angle of groove is shown.

df/dR_b,	df/dR_a,	df/dD,	df/dt,
–48.5	–16.3	0.8	4.0
df/dR_c,	$df/d(dr)$	df/φ, MHz/degree	
–3.9	–28	–0.42	

6. ELECTRIC AND MAGNETIC FIELDS ON CELL SURFACE

For the evaluation of dielectric strength of structure it is necessary to calculate electrical and magnetic fields on the surface from the outlines, showed in Fig.3 by bold lines. The results of calculations for the structure with the peripheral recesses are shown bellow in Table 3. Structure has following geometric dimensions: D=33.31 mm, R_a=21.5 mm, t=5.25 mm, $R_c=t/2$, dr=1 mm, φ=65°, R_b=55.03 mm.

Since to account field on the structure surface precisely is impossible, calculations were performed at different distances from the surface. For determining the maximum value of field on the surface the extrapolation of calculation data was used.



a *b*

Fig.3. Outlines for field maximal value calculation

The results of the calculations of maximum field at the deflecting structure are given in Table 3.

Table 3.

Calculation results of field maximal value

P, MW	$E_{max2}(0)$, MV/m		$H_{max2}(0)$, kA/m
	At outline in Fig.3,a	At outline in Fig.3,b	
2.3	13.29	0.035	44.03
2.6	14.12	0.036	46.82
22.0	41.10	0.107	136.2
24.0	42.93	0.111	142.2
26.3	44.94	0.117	144.5

7. THERMAL REGIME

The calculations of thermal regime of the deflecting structures were carried out. Calculations of temperature distribution in the deflecting structure with two and four tubes of cooling with diameter 4 mm were carried out. The power of losses composes approximately 9.5 W to the cell with the average transmitting power of 812 W. Pulse power is 26.2 MW, pulse duration is 3.1 μs, pulse repetition rate is 10 Hz.

With the use of four cooling channels with rectangular cross-section and flow speed of the cooling water 1.22 m/s temperature maximum change in the structure is equal 1.67°C. For the structure with the peripheral recesses temperature change is 1.5 times less than for the structures with two s stabilization holes at the same speed of cooling water flow.

CONCLUSIONS

All versions of the deflecting structure, given in Table 2, principally can be used for X-FEL. All versions can be realized technologically. Versions c, d and e (see Table 2) have greater electric strength (the smaller value $E_{S\,\max}$), because of the absence of the stabilization holes in diaphragms. These structures also have 1.5 times smaller gradient of temperature. In the version a (see Table 2) for L=35.0 mm the thin wall between the aperture and stabilization hole is obtained. In the version b (see Table 2) for L=45.6 mm the stabilization holes are located closely to the wall of cowling, which complicates the production of roundings on the edges of these holes. The fulfillment of oval aperture completely actually technologically, but will require the additional time and means for its production. Version e is preferable, since it satisfies all requirements for the deflecting structures X-FEL and it is most simple technologically. For this version of the deflecting structure the calculated maximum values of electrical and magnetic field gradient on the surface are 14 mV/m and 47 kA/m, respectively, with the input power of 2.6 MW.

The authors express gratitude to L.V. Kravchuk, V.V. Paramonov, M. Huening and F. Stephan for the useful discussions.

REFERENCES

1. M. Altarelli, R. Brinkmann, M. Chergui, et al. XFEL Technical Design Report// *DESY 2006-097*. 2006, p.11.
2. R. Akle, B. Lentson, P. Emma, et al. A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics // *SLAC-PUB-8864*. June, 2001, p.3.
3. D. Denisenko, V. Paramonov. The Transverse Deflection Structure for X-FEL Numerical Simulation? Analysis and results // *Proc. RuPAC 2008*. Russia, Zvenigorod. 2008, p.37.
4. N.P. Sobenin, B.V. Zverev. *Electrodynamic Characteristics of Accelerating Cavities.* London: "Foundation for International Scientific and Education Cooperation", 1999, p.98.
5. O.A. Valdner, N.P. Sobenin, B.V. Zverev, I.S. Shchedrin. *Disc loaded waveguides. Manual.* M.: "Energoatomizdat", 1991, p.87.

Статья поступила в редакцию 07.09.2009 г.

ДЕФЛЕКТОР НА БЕГУЩЕЙ ВОЛНЕ ДЛЯ ЛАЗЕРА НА СВОБОДНЫХ ЭЛЕКТРОНАХ

А.А. Анисимов, В.И. Каминский, М.В. Лалаян, Н.П. Собенин, А.А. Завадцев

Для системы измерения длины и эмиттанса электронного сгустка в лазере на свободных электронах рассмотрены как известная конфигурация в виде круглого диафрагмированного волновода с двумя отверстиями для стабилизации плоскости поляризации волны, так и новые варианты дефлектора: с двумя выемками в обечайке и с овальной формой отверстия связи.

ДЕФЛЕКТОР НА ХВИЛІ, ЩО БІЖИТЬ, ДЛЯ ЛАЗЕРА НА ВІЛЬНИХ ЕЛЕКТРОНАХ

А.А. Анісімов, В.І. Камінський, М.В. Лалаян, Н.П. Собенін, А.А. Завадцев

Для системи виміру довжини і еміттанса електронного згустку в лазері на вільних електронах розглянуті як відома конфігурація у вигляді круглого діафрагмованого хвилеводу із двома отворами для стабілізації площини поляризації хвилі, так і нові варіанти дефлектора: з двома виїмками в обичайці і з овальною формою отвору зв'язку.