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ЦЕНТРАЛЬНЫЙ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ИНСТИТУТ ИНФОРМАЦИИ И ТЕХНИКО-ЭКОНОМИЧЕСКИХ ИССЛЕДОВАНИЙ ПО АТОМНОЙ НАУКЕ И ТЕХНИКЕ

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THE DEPENDENCE OF MAIN PARAMETERS OF SRS ON THE LATTICE STRUCTURE

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The investigation results of the dependence of main parameters of the designed synchrotron radiation source on the lattice structure for Yerevan Physics Institute are presented. A choice of the criterion optimization is discussed.

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ЗАВИСИМОСТЬ ОСНОВНЫХ ПАРАМЕТРОВ ИСТОЧНИКОВ СИНХРОТРОННОГО ИЗЛУЧЕНИЯ ОТ СТРУКТУРЫ ЯЧЕЙКИ ПЕРИОДИЧНОСТИ

Представлены результаты исследования зависимости основных параметров проектируемого источника синхротронного излучения для Ереванского физического института от структуры ячейки периодичности. Обсуждается выбор критериев оптимизации.

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At present the electron storage rings, dedicated as a synchrotron radiation source (SRS) are designed and built in many accelerator centres. The main parameters of such facilities are: the brightness of the source, the characteristic wave-length λ_c the number of independent radiation ports, the beam life-time, etc.

These parameters are formed by various systems of the storage ring. One of the most important systems of the ring, which defines the values of these main parameters is the magnetic system. This paper deals with the main criteria, which permit to choose the lattice structure and betatron numbers in order to achieve the optimal values of the above mentioned SRS parameters. The investigation of the dependence of this parameter on the lattice structure and tune values are performed based on the design of Yerevan Physics Institute synchrotron radiation source.

The Main Optimization Criteria

1. The SRS Brightness

According to [3], this parameter determined as the photon density at the origin of coordinates of the phase space(x,x', y,y') of an equivalent SR source, is inversely proportional to the horizontal emittance Ex of the beam at given energy E_0 and bending radius ρ. The dependence of Ex^{-1} on the betatron tune values ν_x and ν_z for the FODO structure is finely described by the parameter $\xi = \nu_x^2 / \langle \beta_x \rangle$ with $\langle \beta_x \rangle = \frac{1}{2}(\beta_{x max} + \beta_{x min})$ where β_x is the betatron function. As is shown in [3,4] the maximal brightness of the SR source for the FODO structure is achieved when the horizontal and vertical phase advance per cell is $\mu_x = 131^\circ$ and $\mu_z = 110^\circ$, respectively. In general Ex strongly depends on the lattice structure, too. This permits to increase the brightness of SR source by optimizing both the lattice structure and betatron tune values.

2. The Power of RF System

The required power of storage ring RF system is defined by the peak RF voltage $\hat{V}$ which is necessary to compensate the energy loss U_0 per turn. This RF voltage is given by [1]

$$\hat{V} = \frac{U_0}{e \sin \varphi_s},$$

where e-is the electron charge, φ_s is the synchronous RF phase angle which is determined from

$$\frac{\epsilon_{max}^2}{2\sigma_\epsilon^2} = \frac{(2 + \frac{dR}{\rho})E_0}{\alpha K E_1} F(\varphi_s). \tag{2}$$

Here $F(\varphi_s)$ is the monotone decreasing function [1] σ_ϵ is the mean square energy fluctuation, ϵ_{max} is the maximum energy deviation, R is the mean radius, K is the harmonic number, $E_1 = 1{,}08.10^3$ ev, α is the compaction factor defined by means of the integral over the bending magnets:

$$\alpha = \frac{1}{2\pi R\rho} \oint_{Mag} \eta(\bar{s})\, d\bar{s} \tag{3}$$

where $\eta(s)$ is the off-energy function. The ratio $\epsilon_{max}/2\sigma_\epsilon$ is taken such as the quantum beam life-time, limited by energy oscillation

$$\tau_q^\epsilon = \frac{\tau_\epsilon}{2} \frac{2\sigma_\epsilon^2}{\epsilon_{max}^2} \exp(\epsilon_{max}^2/2\sigma_\epsilon^2), \tag{4}$$

be greater than the designed overall life-time [1,2].

It is seen from (1), (2) that the less is the compaction factor α , the higher is the acceptable value of ψ_s and,hence the less the required power of the RF system

3. The Aperture of Vacuum Chamber

The R.M.S. size of the electron beam in the storage ring is defined as [1]

$$\sigma_x^2 = \frac{C_q \gamma_0^2}{\rho} \left[\frac{H_{mag}\beta(s)}{1 - \frac{\alpha R}{\rho}} + \frac{\eta^2(s)}{2 + \frac{\alpha R}{\rho}} \right] \tag{5}$$

where γ_0 is the Lorenz factor, $C_q = 3.84 \cdot 10^{-13}$ m and

$$H_{mag} = \frac{1}{2\pi\rho} \oint_{Mag} \frac{1}{\beta} \left(\eta^2 + (\beta\eta' - \tfrac{1}{2}\beta'\eta)^2\right) ds \tag{6}$$

The formula (5) is independent of the finite aperture of the vacuum chamber A, the presence of which limits the life-time of the beam. That's why the chamber aperture is taken such as to obtain the quantum life-time due to the betatron oscillations

$$\tau_q = \frac{\tau_x}{2} \frac{2\sigma_{x\,max}^2}{A^2} \exp\left(A^2/2\sigma_{x\,max}^2\right), \tag{7}$$

will be greater than the overall designed time, where τ_x is the betatron oscillation damping time. Using (7) one can write for the given τ_q :

$$A = K_1 \sigma_{x\,max} \tag{8}$$

where K_1 is the proportionality factor which should exceed 10 [1] No less important for obtaining the limitations on the length of quadrupole L is the problem connected with exact determination of constant magnetic field gradient within the given aperture. It was shown empirically [5] that for the nonlinearity less than 1% within 75% of the lens aperture the condition $L/A \geqslant 8.2$ should be met, taking into account (8)

$$L \geqslant 8.2\, K_1 \sigma_{x\,max} \tag{9}$$

One can see from (8) and (9) that small values of $\sigma_{x\,max}$ reduce the required "good" field aperture and allow to decrease both the aperture of the vacuum chamber and the length of quadrupole lenses.

4. Tolerances

For the stable operation of the storage ring it is necessary to soften the tolerances for sustaining the parameters near the calculated values, as the real magnetic system may be performed only with finite accuracy. These tolerances are also the function of the lattice structure. The most important of them are the transverse displacement of quadrupole lenses and the errors of their gradients, which lead to distortions of the equilibrium orbit and tune shifts, respectively.

The magnitude of these tolerances may be estimated by means of the following approximate formulae [5]

$$\delta U = \frac{2B\rho}{L} \mathcal{D}_u \, \delta U_c \,,$$
$$\delta G = \frac{4\pi B\rho}{L} C_u \, \delta \nu_u \,, \qquad (10)$$

where $U=(X,Z)$, B -is the magnetic field, δU, δG are the tolerances for rms values of the lens displacement and the gradient errors for the given equilibrium orbit distortion δU_c and tune shift $\delta \nu_u$. The values of $\mathcal{D}_u$ and C_u are defined by:

$$\mathcal{D}_u = |\sin \pi \nu_u| \left(\beta_{u\,max} \sum_{i=1}^{n} G_i^2 \beta_{ui}\right)^{-1/2} ,$$
$$C_u = \left(\sum_{i=1}^{n} \beta_{ui}^2\right)^{-1/2} , \qquad (11)$$

where n- is the number of quadrupole lenses, G_i is the field gradient in the i-th lens, β_{ui} is the mean value of the betatron function in it. According to (10) at given rigidity $B\rho$ large values of $\mathcal{D}_u$ and C_u lead to the softening of these tolerances.

5. Chromaticity.

In order to eliminate dependence of tune shift on the energy spread in the stored beam, sextupole lenses are set. Their length and longitudinal coordinates are chosen to minimize the required strength $S = \frac{1}{B\rho}\frac{\partial^2 B}{\partial x^2}$ which are defined by [7]:

$$S_F = (b_1 a_{22} - b_2 a_{12})/\det(A) \;,$$
$$S_D = (b_2 a_{11} - b_1 a_{21})/\det(A) \;, \qquad (12)$$

Here b_1, b_2 enaluated in [7] are determined by the lattice structure, and the elements of the matrix A are the integrals over the sextupole lenses:

$$A = (a_{ij}) = \begin{pmatrix} \int\limits_{S_F} \eta\beta_x d\bar{s} & \int\limits_{S_D} \eta\beta_x d\bar{s} \\ \int\limits_{S_F} \eta\beta_z d\bar{s} & \int\limits_{S_D} \eta\beta_z d\bar{s} \end{pmatrix} \qquad (13)$$

The strengths of the sextupole lenses are most strongly influenced by $a_{11}a_{22} - a_{12}a_{21}$ which can be approximately evaluated by means of the expression

$$\ae = \eta_{max}\eta_{min}(\beta_{xmax}\beta_{zmax} - \beta_{xmin}\beta_{zmin}) \qquad (14)$$

It should be noted that according to (12) the sextupoles can't be placed on sections with $\eta = 0$ because they lead to the unlimited lens strength. The value of $\ae$ is determined by the lattice structure and betatron tunes ν_x, ν_z. That's why the optimization of the lattice structure requires the minimization of the sextupole lens strength.

Besides the above mentioned main criteria, when optimizing the lattice structure it's necessary to take into account the ratio of the orbit length to the total length of the bending magnets and quadrupole lenses. This parameter determines the lengths of straight sections, which are necessary for the arrangement of sextupoles, kicker and septum magnets of the control system, etc.

5. The Computation Program

In order to calculate the main parameters of the storage ring a FORTRAN-based program OPTIM was used. As varied parameters the lattice structure and the betatron tune ν_x, ν_z were chosen. To examine arbitrary lattice structures a set of numbers $N(NN)$ is introduced, which gives the sequence of the elements: bending magnets, quadrupoles, sextupoles, ets. The calculation of machine parameters is performed in four steps.

1) For given betatron tune values, a system of two transcendental equation in the gradient of quadrupole lenses are determined.

2) The betatron and off-energy functions and their derivatives are calculated. In order to simplify the calculations an additional matrix $M_t(S)$ is introduced, that has the form of that element in which the amplitude functions are computed. It permits to reduce the error accumulation due to large number of equipartition. The length of the additional element L_t is defined as

$$L_t = L_{el} + \Delta S \ , \qquad (15)$$
$$L_{el} = L_{el} - \Delta S \ ,$$

where L_{el} is the length of the real element, ΔS is the azimuthal step size.

3) All the integral characteristics are calculated, including the natural beam size σ_x , the momentum compaction factor α , damping coefficients, chromaticity, etc. The introduced arrays $M(NN)$ and $BL(NN)$ give the number of equipartition of I-th elements, $M(I)$ and its length $BL(I)$, which allows to calculate all the integrals with desired accuracy by decreasing the azimuthal step $\Delta S = BL(I)/M(I)$.

4) The calculations of the sextupoles, kicker magnets, synchronous phase, Toushek's life-time, etc.

5. The Optimization of the Lattice Structure for the Electron Storage Ring of Yerevan Physics Institute

Four main lattice structures were chosen for the investigation of the behaviour of above mentioned parameters on the lattice structure for Yerevan electron storage ring ERSYNE-1,5. The calculations have been carried out with the following design parameters of storage ρ = 3,31m R = 10m, E_0=1,8 GeV with the bending magnet and quadrupole lens lengths l_m = 1,3m, l = 0,4, respectively. The calculation results are presented in Table 1.

The FOBODOBO structure is shown in fig 1 with the amplitude functions, calculated for the betatron tune values ν_x =3,25 and ν_z = 2,15, corresponding to the maximum brightness for the given number of cells, N=8. This version is noted for small field gradient with the minimum number of the quadrupoles, which decreases the value L_R/L_c and allows to have two long straight sections in lattice. The sextupole lenses have small values, too. However, a large beam size requires a large aperture of the vacuum chamber and respectively the increasing of the quadrupoles length. Simultaneously, the large value of α increases the required rf system power. The source brightness is the worst among the versions under investigation.

In Fig.2 together with corresponding lattice amplitude functions we show the OFOBODO structure which allows to have 16 cells in the orbit with slight decrease in the L_R/L_c ratio.

The choice for optimum frequencies $\nu_x = 4,25$ and $\nu_z = 3,15$ was stipulated by the necessity to have possibly smaller field gradients in the quadrupoles. In this version some criterial parameters are considerably improved: smaller values of σ_{xmax} require respectively smaller good field region in the magnets, the small value of α decreases the required rf system power, small beam emittance increases the SRS brightness. As is seen from Table I, the tolerances for transverse displacement for the given version are the weakest among the discussed ones, But due to the comparably small length of long straight sections, the sextupoles may be arranged after ? period, as is shown in fig.2. The calculations indicate that due to small $\varkappa$ this arrangement of the sextupoles gives the sextupole strength up to 20^{-3}m. The remaining eight straight sections may be used for the arrangement of rf cavities, kicker and septum magnets, etc.

The triplet FDF arrangement is shown in fig.3 with the calculated amplitude functions for the betatron tune values $\nu_x = 3,25$ and $\nu_z = 2,15$. This lattice type with the long straight section $L_o = 2,15$m. make this version most suitable for the installation of wigglers and undulators. A useful reduction is achieved both in the emittance E_x and in the momentum compaction factor α . The configuration of the vertical betatron function is quite suitable for an undulator, as its value remains constant through the long straight section. On the other hand, the ratios between the horizontal and vertical beta values imply that the chromaticity control is likely to be tricky. Besides, the quadrupole have high field gradient. The calculations show that criterial para - meters for the FDF system is better than for DFD.

For an achromatic arc lattice it is required that the off-energy function η and its derivative η' must be zero, everywhere, except the region between two bending magnets. Such an achromatic arc lattice is shown in fig.4. Here we also present the calculated amplitude functions for the tune values ν_x = 6,25 and ν_z = 2,15 which are located in the second range of the stability. The criterial parameters (see table 1) for an achromatic arc lattice are better. However, there are a lot of drawbacks in this type of lattice:

1) the operating range of ν_x and ν_z is very small and the storage ring is very sensitive to errors.

2) the chromaticity is very difficult to be controlled, due to the shape of the betatron function.

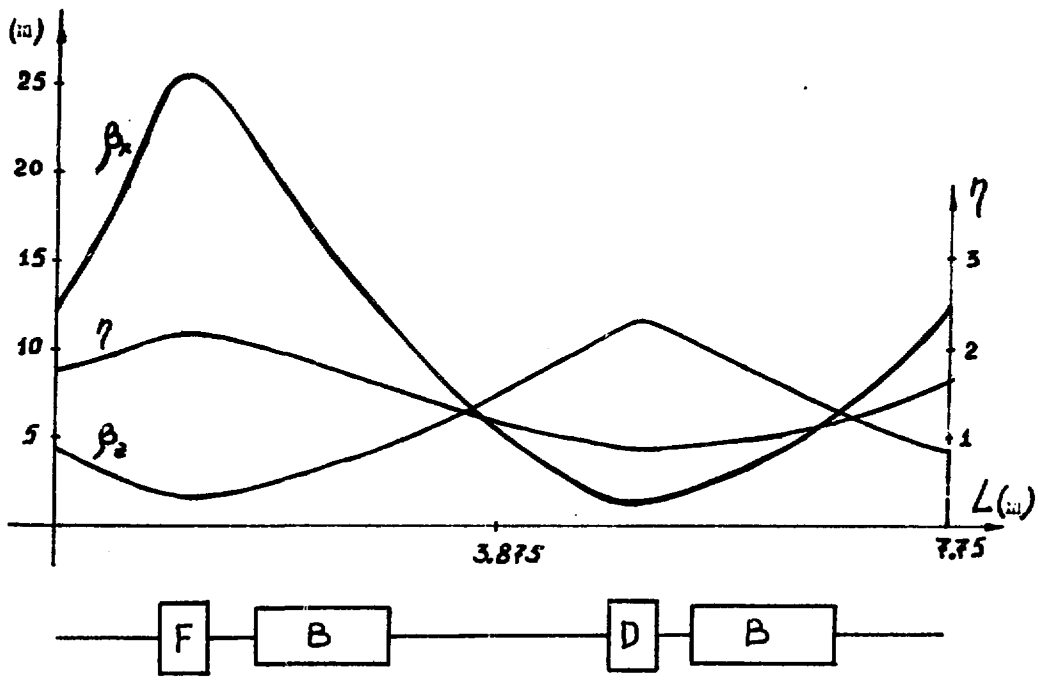
3) there is a little place for the sextupole, kicker and septum magnets.

4) the gradient values in the quadrupoles is high.

According to table 1 an optimal lattice structure is OFOBODO type. However, due to the small straight section, its performance may cause some technical and technological difficulties

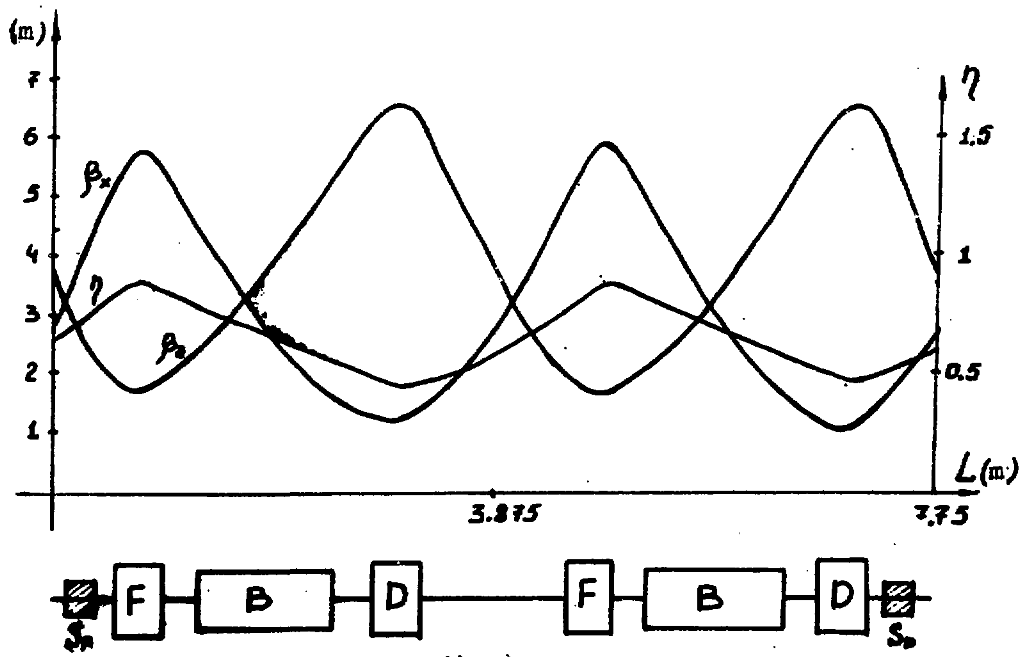
Table 1

Lattice structure	ν_x / ν_z	G_{max} (T/M)	$\varkappa$	L_0 (M)	$\beta_{x\,min}^{\,max}$ (M)	$\beta_{z\,min}^{\,max}$ (M)	η_{min}^{max} (M)	ξ	α	$\sigma_{x\,min}^{\,max}$ (MM)	D_z^x $10^{-3}T^{-1}$	C_z^x (M/T)
FOBODOBO	3.25 2.15	7.6	438	2x1.775	20.6 0.76	11.7 1.9	2.08 0.88	0.99	0.127	5.42 1.2	21 13.2	0.312 0.182
OFOBODO	4.25 3.15	12	14	1.175	5.74 1.17	6.46 1.68	0.87 0.45	5.2	0,054	1.34 0.63	13.8 22	0.123 0.143
FDF	3.25 2.15	14.8	86	2.15	5.3 2.0	15.9 3.15	1.24 0.89	2.89	0.095	2.1 1.33	11.2 55.1	0.116 0.247
Achromatic lattice	6.25 2.15	23.4	-	2x0.95	12.3 0.5	30.8 1.22	0.58 0	6.1	0.0083	0.94 0.215	44.2 138.8	0.265 0.6



(m)
25
20
15
10
5
η
3
2
1
L(m)
3.875
7.75
F
B
D
B

Fig.1.



(m)
7
6
5
4
3
2
1
η
1.5
1
0.5
L(m)
3.875
7.75
F
B
D
F
B
D

Fig.2.

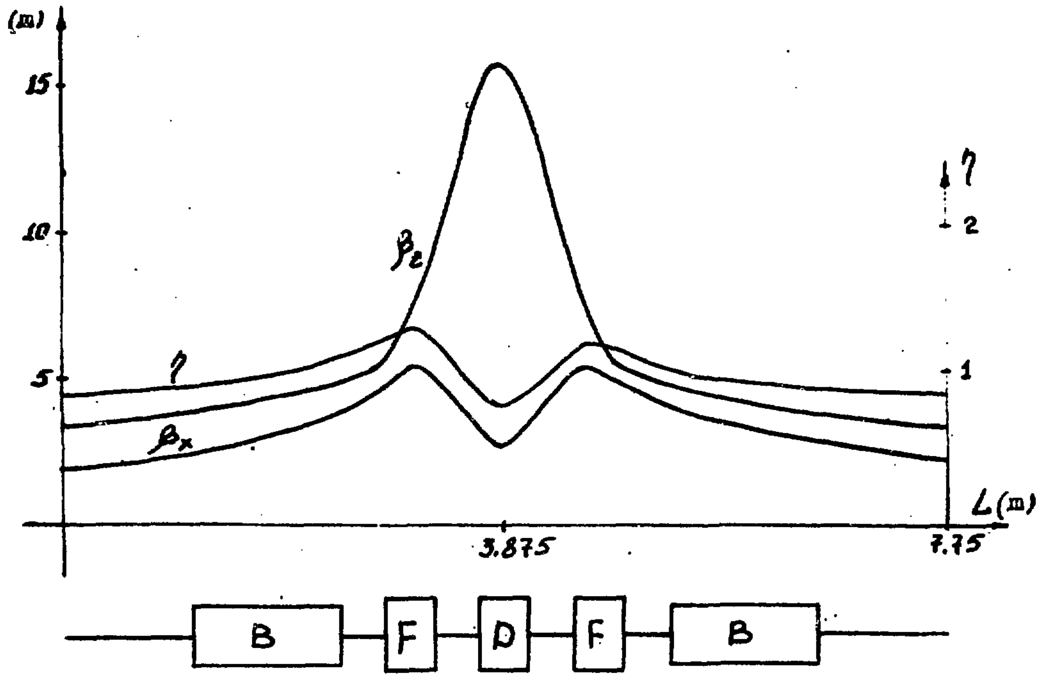

(m)
15
10
5
η
2
1
β_z
η
β_x
L(m)
3.875
7.75
B
F
D
F
B

Fig.3.

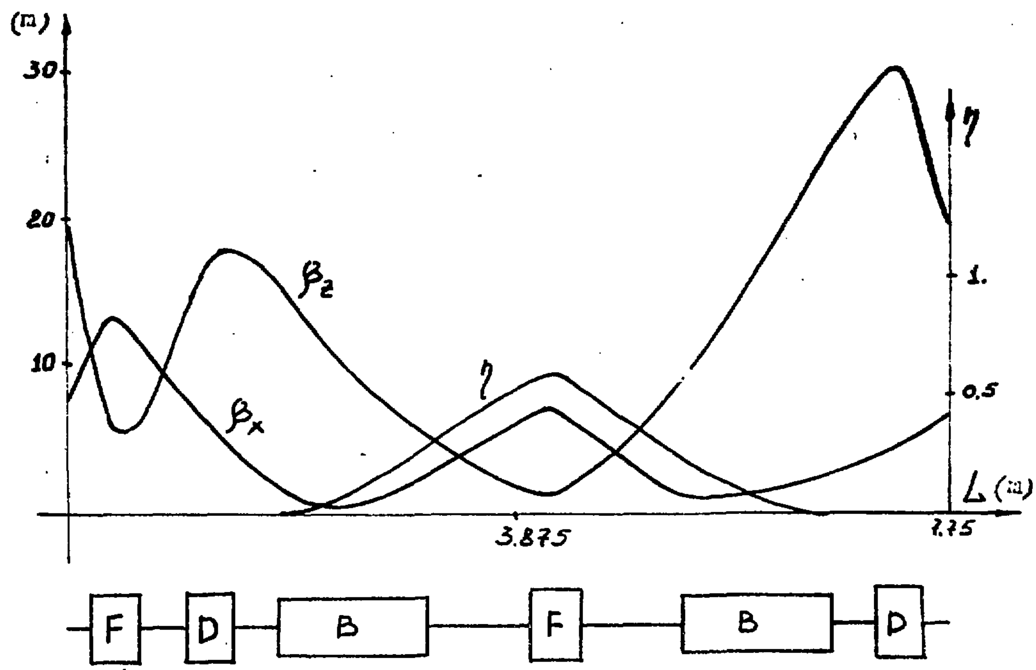

(m)
30
20
10
η
1.
0.5
β_z
β_x
η
L(m)
3.875
7.75
F
D
B
F
B
D

Fig.4.

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