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## Linac-Ring Type $\phi$ Factory of Basic and Applied Research

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### Abstract

In this paper, main parameters for linac-ring type collider designed for producing  $\phi$  particles copiously are estimated and the potential of this machine in particle physics research is investigated. Moreover, parameters for free electron laser and synchrotron radiation obtained from electron linac and positron ring, respectively, are determined and applications of these radiations are summarized.

### 1. Introduction

The center of mass energy  $\sqrt{s}$  needed to produce  $\phi$  particles is about 1 GeV. In this study the main parameters of two linac-ring type collider options are given: one with 125

MeV linac electron beam and 2 GeV positron beam, another with 250 MeV linac electron beam and 1 GeV positron beam. Main reason for designing a collider as linac-ring type machine is the possibility to increase luminosity by one or two orders with respect to standard  $\phi$  factories. Today the highest luminosity among the standard (ring-ring type)  $\phi$  factories is owned by  $DA\phi NE$  with  $L = 5 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$  [1]. The proposed collider will have the opportunity to reach luminosity  $\sim 10^{34} \text{cm}^{-2} \text{s}^{-1}$ .

With such an accelerator a great number of neutral and charged  $K$  mesons ( $> 10^{11}$  per working year), produced as a result of decays of  $\phi$  mesons, can be investigated. The importance of  $K$  mesons study is obvious: for example, in the investigation of CP-violation (matter-antimatter asymmetry) in neutral  $K$  meson decays.

The proposed accelerator complex will give opportunity to perform a large spectrum of applied research: the positron ring can be used as a third generation synchrotron radiation (SR) source and a Free Electron Laser (FEL) can be constructed at the base of the main electron linac.

In the following section we present a general overview of a linac-ring type  $\phi$  factory. The main parameters of the proposed machine are estimated in Section III. Then, in Section IV physics search potential of the collider is briefly discussed. Parameters of SR and FEL photon beams are estimated in Sections V and VI, respectively. We also list the possible applications of these beams in different fields of science and technology in Section VII. Finally, in Section VIII we give some concluding remarks.

## 2. General Overview

The general scheme of the proposed complex is given in Figure 1. Electrons accelerated in the main linac up to energies of 250 (125) MeV are forwarded to the detector region where they collide with positrons from main ring, or turned out to the undulator region where an FEL beam is produced.

On the other side electrons, accelerated in a small linac, are forwarded to the conversion region where the positron beam is produced. Positrons are accumulated in the booster and, after some beam gymnastics, are forwarded to the main ring and accelerated up to energies 1(2) GeV. Wigglers installed in two regions will provide SR for applied research.

## 3. Main Parameters of Linac-Ring Type $\phi$ Factory

The usage of linac-ring type colliders as particle factories has been widely discussed during the last decade. Below we list some proposals with corresponding references:

- i) B Factory [2],
- ii)  $c\text{-}\tau$  Factory [3],
- iii) Z Factory [4].

The main advantages of linac-ring type machines are: the possibility to achieve higher luminosities with respect to standard ring-ring type particle factories and asymmetric kinematics. Of course, LR type  $\phi$  factory is the most compact one because of lowest center-of-mass energy.

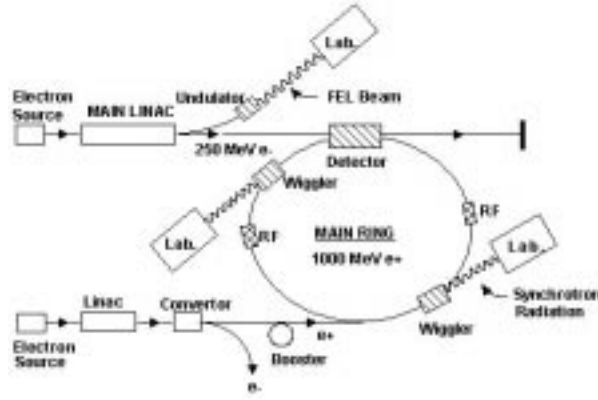


Figure 1. The general scheme of the proposed complex.

The main parameters of the proposed machine are given in Table 1 for two different choices of electron and positron beam energies. Below we present several illuminating notes.

Table 1. Main Parameters of the  $\phi$  factory

Electron beam energy (MeV)	125	250
Positron beam energy (MeV)	2000	1000
Center of mass energy (MeV)	1000	1000
Radius of ring (m)	50	30
Acceleration gradient (MV/m)	12.5	12.5
Length of main linac (m)	10	20
Number of particles in electron beam ( $10^{10}$ )	0.04	0.02
Number of particles in positron beam ( $10^{10}$ )	10	20
Collision frequency, $f$ (MHz)	30	30
Number of bunches in ring, $k$	32	19
Electron current (mA)	1.92	0.96
Positron current (A)	0.96	0.48
Energy loss /turn, $\Delta E_{e^+}$ (MeV)	0.03	0.003
Fractional energy loss of the electrons, $\delta$ ( $10^{-4}$ )	2	1
Beam size at the collision point, $\sigma_{x,y}$ ( $\mu\text{m}$ )	1	1
Beta function at IP, $\beta_{x,y}$ (cm)	0.25	0.25
Bunch length, $\sigma_z$ (cm)	0.1	0.1
Luminosity, $L$ ( $10^{34}\text{cm}^{-2}\text{s}^{-1}$ )	$\simeq 1$	$\simeq 1$

Electron bunches accelerated in main linac are used only once for collisions. On the other hand, positron bunches must be reused numerous times, therefore, the stability of positron beam is very important. The condition of stability is given by

$$n_{e^-} = 8.7 \times 10^8 \cdot E_{e^+} [GeV] \cdot (\sigma [\mu m])^2 \cdot (\beta^* [cm])^{-1} \cdot \Delta Q, \quad (1)$$

where  $n_{e^-}$  is the number of particles in electron bunch,  $E_{e^+}$  is positron beam energy,  $\sigma$  is the transverse size of the beams and  $\beta^*$  is the amplitude function at the collision point,  $\Delta Q$  is tune shift caused by collision. Empirically,  $\Delta Q \leq 0.06$  for lepton beams stored in rings. In principle, this upper limit taken from experiments done in usual ring-ring type  $e^+e^-$  colliders can be higher for linac-ring type machines. In this paper we use the conservative value  $\Delta Q \leq 0.06$ .

Synchrotron radiation resulting from bending magnets used in ring type accelerators causes a decrease in beam energy. Energy loss happening as a result of this radiation in every tour is given by

$$\Delta E_{e^+} [MeV] = 0.0885 \cdot (E_{e^+} [GeV])^4 \cdot (R [m])^{-1} \quad (2)$$

where  $R$  is radius of the ring.

The fractional energy loss of electrons in positron beam field is given by

$$\delta = (n_{e^+} [10^{12}])^2 \cdot (\sigma_z [cm])^{-1} \cdot (\sigma_x [\mu m] \cdot \sigma_y [\mu m])^{-1} \cdot E_{e^+} [TeV], \quad (3)$$

where  $n_{e^+}$  is the number of particles in one positron bunch,  $\sigma_{x,y}$  are the vertical and horizontal transverse sizes of the beam at the collision point (in our case  $\sigma_x = \sigma_y = \sigma$ ),  $\sigma_z$  is the bunch length.

Electron current is given by

$$I_{e^-} [mA] = 1.6 \times 10^{-19} \cdot n_{e^-} \cdot f, \quad (4)$$

where  $f$  is the collision frequency. Positron current in the ring is

$$I_{e^+} [A] = 1.6 \times 10^{-19} \cdot k \cdot n_{e^+} \cdot (c/2\pi R), \quad (5)$$

where  $k$  is the number of positron bunches in the ring and  $c$  is the speed of light.

#### 4. Physics Search Potential

Quantum numbers of  $\phi$  mesons produced as a resonance in  $e^+e^-$  collisions are  $I^G(J^{PC}) = 0^-(1^{--})$ . Mass is  $m_\phi = 1015.413 \pm 0.008$  MeV and total decay width is  $\Gamma = 4.43 \pm 0.05$  MeV [5]. Fundamental decay channels and branching ratios are given in Table 2.

Since deviation of the center-of-mass energy of  $e^+e^-$  collisions is smaller than the total decay width of  $\phi$  meson, cross-section in the  $\phi$  resonance region can be taken as

$$\sigma = (12\pi/m^2) \cdot (\Gamma_c/\Gamma) \simeq 4.4 \times 10^{-30} cm^2. \quad (6)$$

In the proposed complex  $4.4 \times 10^{11} \phi$  meson,  $2.2 \times 10^{11} K^+K^-$  pairs and  $1.5 \times 10^{11} K_L^0 K_S^0$  pairs can be produced in a working year ( $10^7$ s). Fundamental problems of particle physics such as CP violation, rare decays of K mesons etc. can be investigated with highest statistics. Moreover, kinematical asymmetry can be advantageous for measuring

neutral K meson's oscillations and CP violation parameters. Detailed analysis of physics search potential will be done in forthcoming publications.

**Table 2.** Comparison of event numbers in DAΦNE and proposed collider

Decay channels	Branching ratios	N (DAΦNE)	N (LR type $\phi$ Factory)
$K^+K^-$	0.495	$1.1 \cdot 10^{10}$	$2.2 \cdot 10^{11}$
$K_L^0 K_s^0$	0.344	$7.6 \cdot 10^9$	$1.5 \cdot 10^{11}$
$\rho\pi$	0.155	$3.4 \cdot 10^9$	$6.9 \cdot 10^{10}$
$\eta\gamma$	$1.26 \cdot 10^{-2}$	$2.8 \cdot 10^8$	$5.6 \cdot 10^9$
$\pi^0\gamma$	$1.31 \cdot 10^{-3}$	$2.9 \cdot 10^7$	$5.8 \cdot 10^8$
$e^+e^-$	$2.99 \cdot 10^{-4}$	$6.6 \cdot 10^6$	$1.3 \cdot 10^8$
$\mu^+\mu^-$	$2.5 \cdot 10^{-4}$	$5.6 \cdot 10^6$	$1.1 \cdot 10^8$
$\eta e^+e^-$	$1.3 \cdot 10^{-4}$	$2.9 \cdot 10^6$	$5.8 \cdot 10^7$
$\pi^+\pi^-$	$8 \cdot 10^{-5}$	$1.8 \cdot 10^6$	$3.6 \cdot 10^7$
$\eta(958)\gamma$	$1.2 \cdot 10^{-4}$	$2.7 \cdot 10^6$	$5.4 \cdot 10^7$
$\mu^+\mu^-\gamma$	$2.3 \cdot 10^{-5}$	$5.1 \cdot 10^5$	$1.0 \cdot 10^7$

## 5. Synchrotron Radiation Facility

Charged particles emit electromagnetic radiation when they accelerate in a circular orbit. This radiation is called synchrotron radiation. Synchrotron radiation is usually a disturbing phenomenon since it causes the particles to lose energy. However, synchrotron radiation has many applications since it has a wide spectrum, including  $x$ -ray. Energy loss with synchrotron radiation is proportional to  $\gamma^4$ , where  $\gamma$  is the Lorentz factor. To change the spectrum of the radiation, either synchrotron ring radius or energy of the positrons moving on the ring should be changed, but both of them are not practical methods. Therefore, photons with higher energy can be produced by using a series of alternating directional equal dipole magnets, called a wiggler. By inserting wigglers on the straight segments of the main ring of the  $\phi$  factory, one can produce synchrotron radiation for applied research.

When one thinks of a whole wiggler, every pole end is designed to have a net neutral effect on the particle path. Photon flux is proportional to the number of magnet poles. Strength parameter of the wiggler magnet is given by

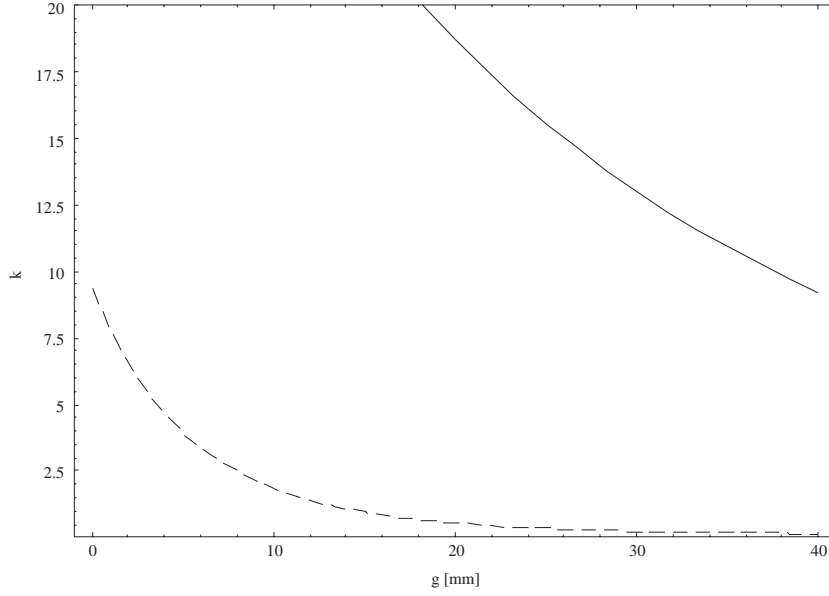
$$K = 0.934 \cdot B_0[T] \cdot \lambda_p[cm], \quad (7)$$

where  $\lambda_p$  is the length between sequential, same directional magnet poles.  $B_0$  is the maximum magnetic field strength on midplane axes and its value for hybrid permanent magnet system is approximately (for  $g \leq \lambda_p$ )

$$B_0 \simeq B_m \exp\left[-\frac{g}{\lambda_p}\left(b - c\frac{g}{\lambda_p}\right)\right], \quad (8)$$

where  $g$  is the vertical distance between magnets,  $B_m$  is the peak value of magnet's field, and  $b$  and  $c$  are constants related to used permanent magnets. If one uses a SiCo type

magnet:  $B_m = 3.33$  Tesla,  $b = 5.47$  and  $c = 1.8$  [6]. Figure 2 shows  $g$  dependence of strength parameter of the wiggler for two values of  $\lambda_p$ .



**Figure 2.** The  $g$  dependence on strength parameter for  $\lambda_p = 33$  mm (Dashed line) and  $\lambda_p = 132$  mm (Solid line).

Power emitted by the wiggler is given by

$$P[kW] = 0.632 \cdot L[m] \cdot I_{e+}[A] \cdot (E_{e+}[GeV])^2 \cdot (B_0[T])^2, \quad (9)$$

where  $L$  is the total length of the wiggler. The power of the designed wiggler's radiation with respect to  $g$  is shown in Figure 3.

Spectral flux and spectral central brightness are given by

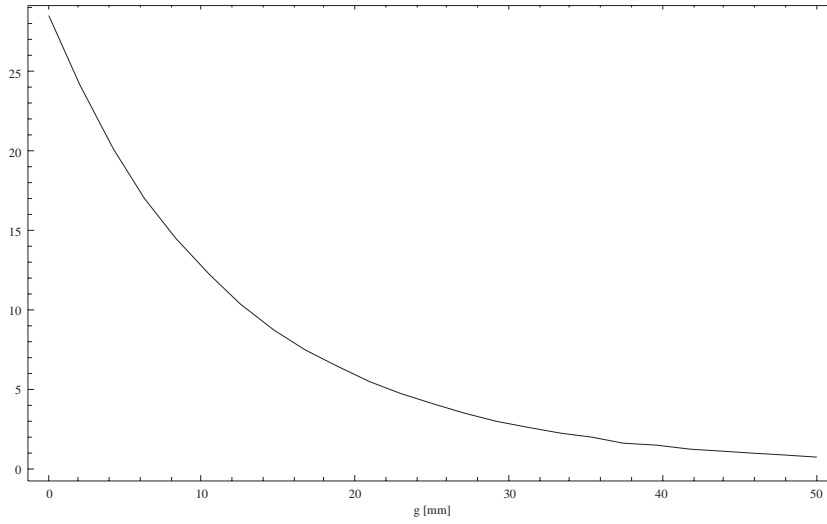
$$I_F[\text{phot./sec} \cdot \text{mrad} \cdot 0.1\% \text{bandw}] = 2.458 \cdot 10^{10} \cdot 2N \cdot I_{e+}[mA] \cdot E_{e+}[GeV] \cdot \frac{E}{E_c} \int_{E/E_c}^{\infty} K_{5/3}(\eta) d\eta \quad (10)$$

and

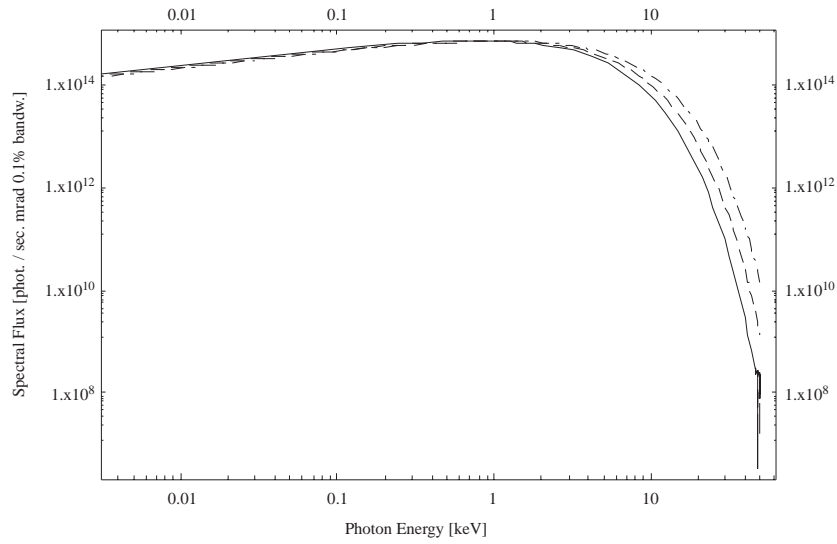
$$I_B[\text{phot./sec} \cdot \text{mrad}^2 \cdot 0.1\% \text{bandw}] = 1.325 \cdot 10^{10} \cdot 2N \cdot I_{e+}[mA] \cdot E_{e+}^2[GeV]^2 \cdot \left(\frac{E}{E_c}\right)^2 K_{2/3}\left(\frac{E}{E_c}\right), \quad (11)$$

where  $E$  and  $E_c$  are photons' energy and critical energy, respectively. Figure 4 and Figure 5 present the spectral flux and central brightness with respect to photon energy for three different  $g$  values. Critical photon energy is defined by

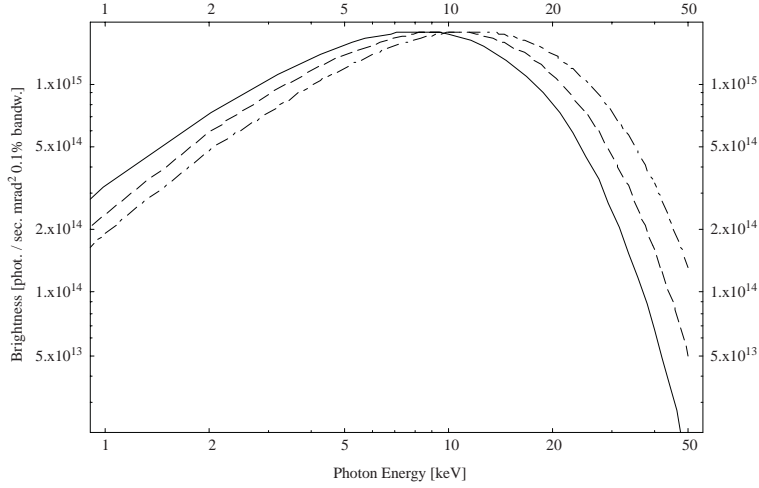




**Figure 3.** The  $g$  dependence on the SR power.



**Figure 4.** Spectral flux of the SR. Solid line:  $g=30$ mm, Dashed line:  $g=25$  mm, Dot-dashed line:  $g=20$ mm.



**Figure 5.** Spectral central brightness of the SR. Solid line:  $g=30\text{mm}$ , Dashed line:  $g=25\text{mm}$ , Dot-dashed line:  $g=20\text{mm}$ .

$$E_c[\text{keV}] = \hbar\omega_c = 0.665 \cdot (E_{e+}[\text{GeV}])^2 \cdot B[\text{T}]. \quad (12)$$

Main parameters of SR facility for two options are given in Table 3.

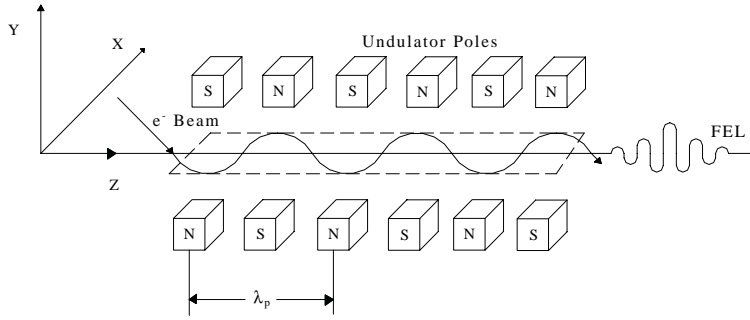
**Table 3.** Main parameters of SR facility

	1	2
Energy (GeV)	1	2
Maximum magnetic field ( $T$ )	1.054	1.054
Current (A)	0.976	0.488
Period (cm)	13.2	13.2
Gap (mm)	30	30
Total length (m)	2.112	2.112
Total radiated power (kW)	1.44	2.90
Critical energy, $E_c$ (keV)	0.700	2.804
Wiggler parameter	12.99	12.99
Spectral flux (Phot/s.mrad $\cdot$ 0.1%bandw)	$4.96 \times 10^{14}$	$5.00 \times 10^{14}$
Spectral central brightness (Phot/s.mrad $^2 \cdot$ 0.1%bandw)	$4.95 \times 10^{14}$	$9.98 \times 10^{14}$

## 6. Free Electron Laser Facility

A Free Electron Laser (FEL) is a mechanism to convert some part of the kinetic energy of relativistic electron beam into a tunable, very bright and monochromatic coherent photon beam by using undulators inserted in the linear accelerators or synchrotrons [7]. A relativistic electron beam oscillates on a sinusoidal path with the help of a undulator

magnet which has an oscillating magnetic field between its poles. As a result an FEL beam is produced (see, Figure 6.)



**Figure 6.** Schematic view of the FEL process.

Wavelength of the obtained FEL beam is dependent on the energy of the electron beam, the period of undulator poles and undulator's K parameter:

$$\lambda_{FEL} = \frac{\lambda_p}{2\gamma_e^2} \left(1 + \frac{K^2}{2}\right) \quad (13)$$

Where,  $\lambda_p$  is the period length of the undulator, and  $\gamma_e$  is the Lorentz factor of the electron beam. Undulator parameter, K, is given by Eqn. (7). For an undulator  $K \simeq 1$  and the first harmonic primary contribution to the radiation. Laser wavelength and energy for a plane undulator in terms of practical units are given as

$$\lambda_{FEL}[\text{\AA}] = 13.056 \frac{\lambda_p[\text{cm}]}{(E_{e-}[\text{GeV}])^2} \left(1 + \frac{K^2}{2}\right) \quad (14)$$

and

$$E_{FEL}[\text{eV}] = 950 \frac{(E_{e-}[\text{GeV}])^2}{\lambda_p[\text{cm}] \left(1 + \frac{K^2}{2}\right)}. \quad (15)$$

The main parameters of the two variations of FEL facility are given in Table 4.

**Table 4.** Main parameters of FEL facility.

	$E_e = 125\text{MeV}$	$E_e = 250\text{MeV}$
Photon energy (eV)	4.07	16.30
Laser wavelength (Å)	3044	761
Beam current (mA)	1.92	0.96
Particle per bunch ( $10^{10}$ )	0.04	0.02
Repetition frequency (MHz)	30	30
Averaged laser beam power (W) for $L = 10$ m	$4.18 \cdot 10^{-3}$	$8.36 \cdot 10^{-3}$
Flux (Phot/(s·mrad·0.1%bandw))	$3.78 \cdot 10^{13}$	$7.56 \cdot 10^{13}$
Averaged brightness (Phot/(s·mrad <sup>2</sup> ·0.1%bandw))	$2.91 \cdot 10^{11}$	$5.81 \cdot 10^{11}$

Magnetic field strength between poles of plane undulators is given by Eqn. (8), and with this the magnetic field is estimated to be 1.48 kG with  $b = 5.47$  ,  $c = 1.8$  ,  $\lambda_p = 33$  mm and  $g = 25$  mm. With these values, the strength parameter of undulator can be obtained from Eqn.(7) as  $K = 0.456$ .

FEL beam flux as a function of energy is given as follows [8]:

$$I_{FEL} = 1.74 \cdot 10^{14} N^2 (E_{e^-} [GeV])^2 I[A] F_n[K] f(n\nu_n), \quad (16)$$

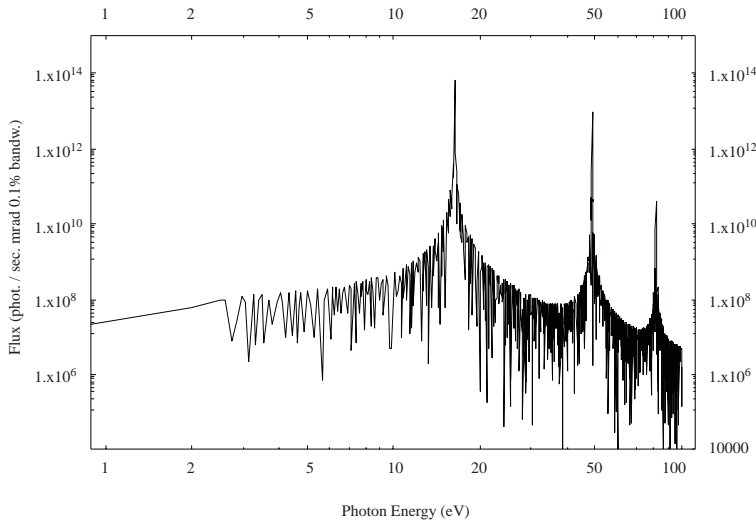
where

$$F_n[K] = \xi n^2 [J_{(\frac{n-1}{2})}(n\xi) - J_{(\frac{n+1}{2})}(n\xi)]^2, \xi = \frac{1}{2} \frac{K^2}{1 + K^2} \quad (17)$$

and

$$f(\nu) = \left(\frac{\sin \nu/2}{\nu/2}\right)^2, \nu_n = 2\pi N \frac{n\omega_1 - \omega}{n\omega_1}, n = 1, 3, 5... \quad (18)$$

Here,  $J_n$  is  $n$ -th order cylindrical Bessel function,  $\omega_1 = E_{FEL}/\hbar$  is the frequency of the first harmonic radiation,  $N$  is the number of undulator poles and  $n$  is the order of harmonics. Figure 7 shows the dependence of FEL flux on photon energy for the  $E_{e^-} = 250\text{MeV}$  option. Here peaks are placed at odd harmonics and maximum values of fluxes are  $7.56 \cdot 10^{13}$ ,  $1.08 \cdot 10^{13}$  and  $9.45 \cdot 10^{11}$  for  $n = 1, 3$  and  $5$ , respectively. The expected average brightness values for the photon beam are given in Table 4.



**Figure 7.** Flux of the FEL beam.

## 7. Application Fields of Synchrotron Radiation and Free Electron Lasers

Synchrotron radiation sources and free electron lasers have a rich spectrum of applications (see, for example, [9]) both in scientific research and industry. Some of them are listed below:

- Atomic and molecular spectroscopy,
- Spectroscopy of atomic and molecular clusters,
- Solid state spectroscopy,
- Physics and chemistry of surfaces and thin films,
- Photochemical processes,
- Biological structure and dynamics,
- Materials and surface processing,
- Multilayer magnetic films,
- The electronic structure of semiconductors,
- Heavy fermion materials and high temperature superconductors,
- Dynamics of catalytic reactions.

Proposed SR source will cover photons wavelengths  $\lambda \geq 0.1\text{\AA}$ , whereas FEL will produce a laser beam with  $\lambda \approx (760 - 3000)\text{\AA}$ . Due to appropriate modifications of wiggler or undulator parameters these regions may be extended. Moreover there is also the possible option of inserting an undulator in the positron ring to obtaining FEL beam. All these topics will be considered in forthcoming publications.

## 8. Conclusion

In this paper we show that sufficiently high luminosities can be achieved in a linac-ring type  $\phi$  factory, with which, the proposed complex may be used in a wide spectrum of applied and technological research. It is for this breadth of usefulness, together with its compactness, the linac-ring type  $\phi$  factory should be considered for inclusion in the National Accelerator Laboratory.

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