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AN INTENSIVE COMPTON SOURCE OF POLARIZED TAGGED HIGH ENERGY GAMMA QUANTA AT SPring-8

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НОВОСИБИРСК

An Intensive Compton Source of Polarized Tagged High Energy Gamma Quanta at SPring-8

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Abstract

In the Proposal is described a facility, producing high energy, intensive, mono- chromatic and polarized γ-beam by Compton scattering of laser photons on the relativistic electrons. The facility can be built at the SPring-8 storage ring and used for a broad range of experiments in the fields of high energy, nuclear and accelerator physics. Main parameters of the facility are:

The γ-beam energies:	up to 3.4 GeV
Intensity of the γ-beam:	up to 10^7 s^{-1}
Energy resolution (by tagging):	13-20 MeV
Polarization of the γ-beam:	100%

Main parts of the proposed facility are described, their principles of operation, parameters, and location are discussed.

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1 Introduction

External γ-beams is an effective instrument for a broad set of the experimental studies in the fields of high energy, nuclear and accelerator physics. Method of Backward Compton Scattering (BCS) of laser light on the high energy electrons in the storage ring is the most advanced method to produce the external γ-beam of high utilization quality. At the present time several facilities based on the method of BCS of laser photons are build in a number of laboratories. Their parameters, and parameters of the facilities, which have already finished their experimental programs are summarized in the Table 1.

At the Budker INP the first BCS γ-beam of undulator photons was observed in 1980 at the VEPP-2M storage ring [10]. In 1982 at the VEPP-4 storage ring the ROKK-1 facility was built [2], which gave name to the series of the ROKK facilities (ROKK is the Russian abbreviation for Backward Scattered Compton Quanta). The ROKK-2 and ROKK-1M started their operation at the BINP in 1987 and 1993 respectively. Description of the ROKK-2 may be found in [3], description of the ROKK-1M in [5].

2 Motivation

At the present time the SPring-8 is the most advanced project from the point of view of the electron beam properties: high intensity and energy, low emittance, semi-continuos electron current. That gives an excellent possibility to build the high quality Compton γ-source.

Facility	LADONE	ROKK-1	ROKK-2	LEGS	ROKK-1M	GRAAL	PMF
Storage Ring	ADONE	VEPP-4	VEPP-3	NSLS	VEPP-4M	ESRF	SIBERIA
Years	1980–91	1982–85	1987-93	1989	1993	1995	1996
Electron energy,GeV	1.5	5.5	2.0	3.0	5.5	5.5	2.5
Beam current,A	0.2	0.01	0.2	0.2	0.02	0.2	0.2
Photon energy,eV	2.41	2.34 2.4	2.41 3.53	2.41 3.41	1.17;2.34 3.53;4.68	2.41 3.54	2.41
Gamma energy,GeV	5–78	120–850	30–140 30–220	50–360	100–1600	100–1600	200
Gamma Flux,s^{-1}	10^5	$2.5 \cdot 10^5$	$3 \cdot 10^6$	$3 \cdot 10^6$	$3 \cdot 10^6$	$10^6 - 10^7$	$10^6 - 10^7$
Monochr. method	coll.,tag	tag	tag	tag	coll.,tag	tag	tag
Energy resolution,%	2–18	2–4	1.5–2	1.5–3	0.2	1	1–3
Reference	[1]	[2]	[3]	[4]	[5]	[6]	[7]

Table 1: Review of the facilities using the BCS method. In the table two methods to make the Compton γ-beam monoenergetic are by tagging (tag) and by collimation (coll.).

Using this Compton γ-source one can provide the wide experimental program in different fields of the experimental physics. Namely:

- For the SR utilization knowledge of the electron beam parameters, such as absolute energy is very important. The Compton facility, working in the "Laser Polarimeter" mode can measure the electron beam energy with the accuracy 10^{-5} see ref. [5]. Electron beam parameters and stability can be also controlled by the BCS facility.
- In the field of high energy physics the facility can be used for different detector systems calibration. Such kind of experiments provided at the ROKK-1M facility allows to make calibration of the Detector KEDR Liquid Krypton Calorimeter Prototype [11] and the Detector KEDR Tagging System [12]. Calibration of the KEK detector [7] CsI calorimeter matrix [7] will be done late of this year. At the ROKK-1M facility the experiment on the photon splitting in the strong Coulomb field of heavy nuclei and Delbrück scattering is carried on now.
- Usage of the polarized γ-beam as an electromagnetic probe opens possibility to provide the wide range of the photonuclear physics experiments with polarized and unpolarized light and heavy nuclei. Experimental program for the nuclear physics is well known [13] and in fact, depends on the types of the detectors, used in experiments.

Detailed discussion of the experimental program for the Compton γ-source goes far out of the frame of this Proposal, and requires participation of the physicists taking part in the project.

3 Backward Compton Scattering

3.1 Main Formula

In this section are given the basic formula, used for calculation made in the Proposal. Maximal γ-quantum energy ω_{max} which can be achieved in the BCS is given by the eq. 1 (c=1):

$$\omega_{max} = \varepsilon \frac{\lambda}{1+\lambda}; \qquad \lambda = \frac{4\varepsilon\omega_o}{m^2} cos^2 \frac{\alpha}{2} \tag{1}$$

where ε and m are the energy and rest energy of the initial electron, ω_o is the energy of the laser photon, α is the electron photon meeting angle. γ-quantum with energy ω_{max} is emitted in the direction of the initial electron momentum. γ-quanta with the energy ω lower than ω_{max} are emitted at the angle θ to the initial electron momentum direction:

$$\omega(\theta) = \frac{\omega_{max}}{1 + \left(\frac{\theta}{\theta_c}\right)^2} \tag{2}$$

where $\theta_c = \frac{m\sqrt{1+\lambda}}{\varepsilon}$ is the characteristic angle of the BCS angular distribution. One can see the unambiguous correlation between the γ-quantum energy ω and its emission angle θ.

The total cross section for the BCS process is described by the Klein-Nishina formula (see [14]) as:

$$\sigma_c = \frac{2\sigma_o}{\lambda}\left\{\left[1 - \frac{4}{\lambda} - \frac{8}{\lambda^2}\right] ln(1+\lambda) + \frac{1}{2}\left[1 - \frac{1}{(1+\lambda)^2}\right] + \frac{8}{\lambda}\right\} \tag{3}$$

where $\sigma_o = \pi\left(\frac{e^2}{m}\right)^2$ is the Thompson cross section. The BCS energy spectra can be written as:

$$\frac{1}{\sigma_c}\frac{d\sigma_c}{d\omega} = \frac{2\sigma_o}{\lambda\sigma_c}\left\{\frac{1}{1-\omega} + 1 - \omega - \frac{4\omega}{\lambda(1-\omega)} + \frac{4\omega^2}{\lambda^2(1-\omega)^2}\right\} \tag{4}$$

Averaged polarization of the BCS γ-quanta does not depend on the polarization of the electron beam. Ordering the initial polarization of the laser light, one can obtain the same type of polarization of the BCS γ-beam. Detailed description of the BCS process and polarization characteristics of the γ-beam are discussed in [15].

3.2 The BCS Energy Spectra

In this section the spectra for the BCS γ-quanta are calculated for some wavelengths of commercial available lasers. All calculations are done according to the formulae (4) for the meeting angle $\alpha = 0$. Non-zero meeting angles are not considered in the Proposal (except section 4.3) because head-on-head electron photon interaction provides the maximal value of ω_{max} and maximal γ-flux at the same laser power due to the longer electron photon interaction area. The initial electron energy ε for all spectra is 8 GeV. Spectra are shown in Fig. 1.

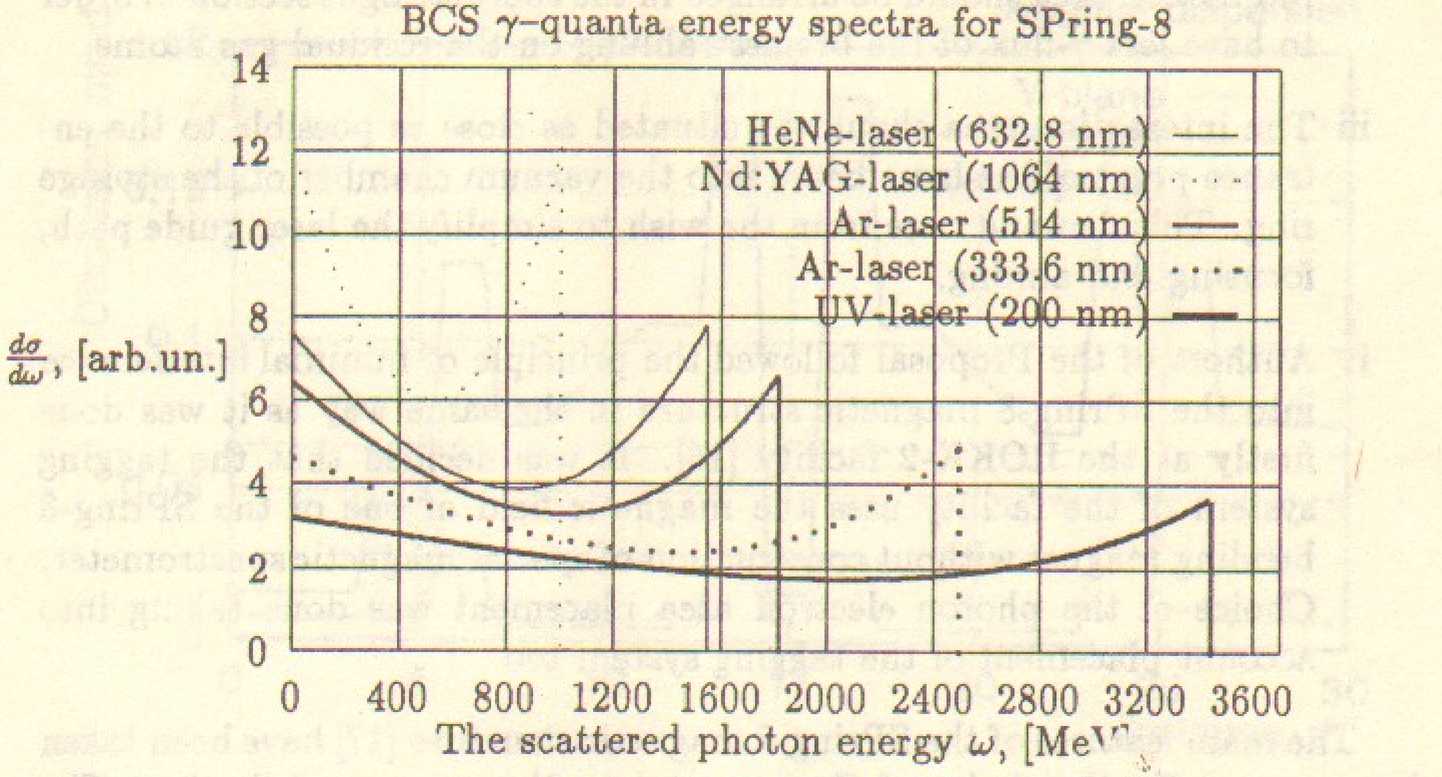

Figure 1: BCS spectra calculated for the several wavelengths of commercial available lasers.

4 Parameters of the BCS Facility at the SPring-8

4.1 Choice of the BCS Interaction Area Placement

In order to choose the best electron photon interaction area in the SPring-8, several factors should be taken into account.

i Size and shape of the BCS γ-beam is determined by its horizontal and vertical angular divergences at the certain distance from the interaction area. These parameters are very significant because they determine luminosity for any further experiments on this γ-beam. The angular divergences of the γ-beam are formed by the square sum of BCS characteristic angle θ_c and the angular divergency σ' in the electron beam. The contribution of the latter should be minimized by choosing a BCS interaction area with the smallest possible angular spreads in the electron beam. It will be discussed in details in the section 4.3.

ii Interaction area should be arranged in the short straight section in order to have less γ-flux of the bremsstrahlung on the residual gas atoms.

iii The interaction area should be situated as close as possible to the entrance point of the laser beam into the vacuum chamber of the storage ring. This demand rises from the wish to simplify the laser guide path, focusing and aiming.

iv Authors of the Proposal followed the principle of minimal interference into the SPring-8 magnetic structure in the same way as it was done firstly at the ROKK-2 facility [16]. It was decided that the tagging system of the facility uses the magnetic field of one of the SPring-8 bending magnet without construction of special magnetic spectrometer. Choice of the photon electron area placement was done taking into account placement of the tagging system too.

The main features of the SPring-8 magnetic structure [17] have been taken into account for the choice of Compton interaction area are following. The storage ring lattice has 24 periods. Each period encompirses two mirror symmetrical Chasman Green cells (CG cell), but four periods have the Straight cell instead of one CG. Straight cell is almost as CG one with the bending magnets removed. The beam profiles are similar in the Straight and CG cells. One CG cell has two bending magnets. So, there are six different bending magnets, where the tagging system can be built. All the rest are in the same conditions as these six from the point of view of storage ring lattice. Let us name them BD1, BD2, BM1, BM2, BS1 and BS2. The letters used for abbreviation means: B for bending magnet, D means that the magnet is in the direct CG cell (in the direct order as it appears in [17]), M means that the magnet is in the mirror symmetrical CG cell (in the inverse order as it appears in [17]), S means that the magnet is in the CG cell which follows the Straight cell, figure shows the number of the magnet along the electron beam trajectory.

It is easy to see, that the BS2 is in the same condition as BD2 from the point of view of the lattice functions. In order to fulfill requirement [i] the Compton interaction area should be placed where the electron beam angular spread is small. In the Fig. 2 one can see the electron beam angular spreads in a direct CG cell. Solid line is for the horizontal coordinate X, long dashed for vertical coordinate Y, horizontal line of short dashes on the plot is the characteristic angle of the Compton scattering θ_c (see section 3.1).

It is necessary to note, that the vertical angular spread in the electron beam is everywhere less than θ_c. In the horizontal plane there are three regions, where the spread is less than θ_c. The third one cannot be taken into account for the organizing of the Compton interaction as it is the beta function bent point in the quadrupole lens, so it is short.

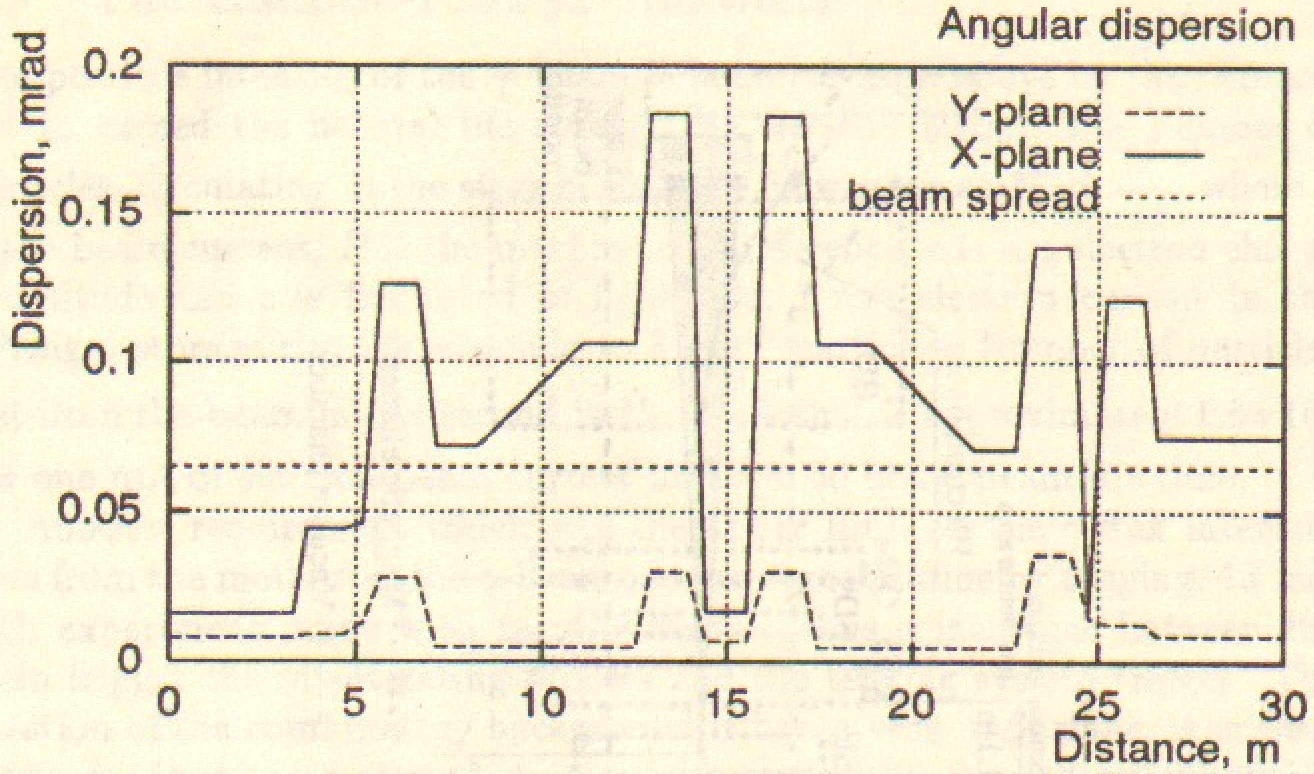

Figure 2: Angular spread in the electron beam. Solid line is along the X-coordinate, long dashed line is along the Y-coordinate. Short dashes show angle equal θ_c.

Among other two regions the first one is in the beginning of the cell, and the second one just in the center. It is clear that the second region matchs the requirements [ii, iii] better. Center of the first region is situated 11 m from the end of the following magnet, where the laser light may be entered in the vacuum chamber. Center of the second region is only 6.7 m from the end of the following magnet. The first region is situated in the 16.53 m straight section, the second is in 7.77 m straight section, that will give more than twice less bremsstrahlung background under the same vacuum conditions. So the best place for the BCS interaction area is the center of the CG cell.

Principal view of the facility is shown in Fig 3.

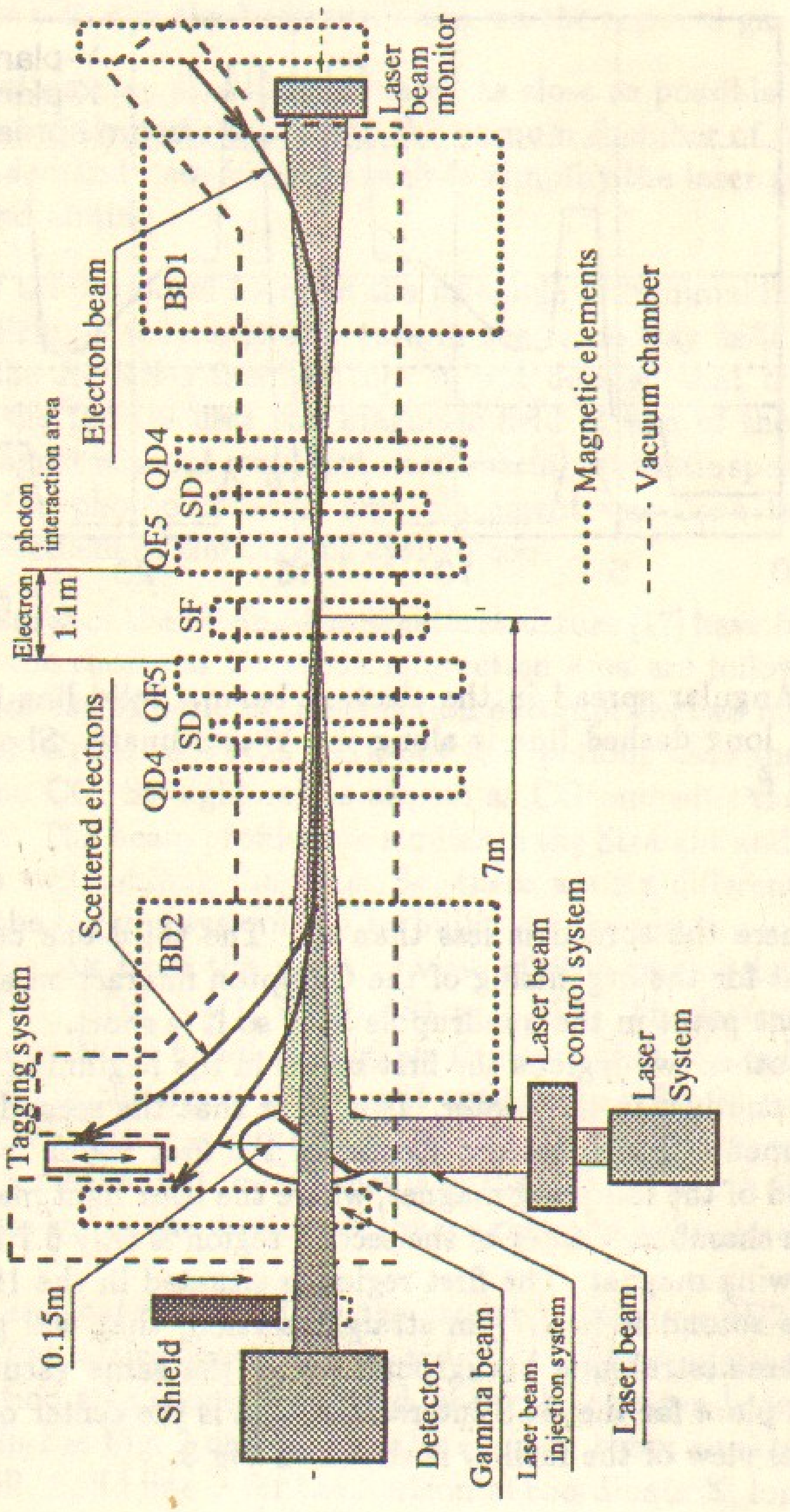

Figure 3: Main elements of the facility.

4.2 The Gamma-Flux Estimations

The possible intensity of the γ-beam is bounded from above by the demand not to exceed the natural life time of the electron beam. The number of particles, circulating in the storage ring can be written as $N_e = \frac{IP}{ec}$, where I is the beam current, P is the machine circumference, e is the electron charge magnitude and c is the speed of light. So, 1 mA electron current in the SPring-8 storage ring corresponds to $3 \cdot 10^{10}$ particles. Number of particles lost from the beam in one second is $\dot{N}_e = \frac{N_e}{\tau}$ that is approximately $1.6 * 10^5$ per one mA of electron beam current and $\tau \approx 50$ hours beam life time.

Another requirement which sets the upper limit on the γ-flux intensity rises from the method of the γ-beam monochromatization by tagging. In fact each experiment made with tagging beam means coincidence between the main trigger the investigating process and the tagging system trigger. The question of the combinatory background is hence very important. It is clear that more than one scattered electrons detected in the tagging system within the resolution time produces such a background. Let the tagging system has resolution time less than time interval between neighbour bunches. Still two electrons scattered from the same bunch cannot be distinguished. In the case of SPring-8 multi-bunch operation mode (n=100 bunchs) the time interval between the neighbour bunchs is $\Delta t = \frac{P}{cn} = 48\ ns$, that corresponds to $2.1 * 10^7$ γ-quanta per second. In fact this number should be smaller because average value of one γ-quantum per bunch means that in significant number of cases more than one electron is scattered according to the Poisson distribution.

So, the reasonable γ-beam intensity is about 10^7 photons per second at 100 mA beam current. That will not significantly decrease the electron beam life time and will give less than one scattering electron per each bunch in the storage ring.

As far as we have fixed the intensity, the next step is to choose the convenient laser system to supply proper light power. At such a small time interval between the neighbour bunchs a continuos operating laser system is more preferable due to its relative simplicity and convenience.

The electron photon luminosity can be written as an integral along the interaction area $[-s; s]$:

$$L = \nu \int_{-s}^{s} \int_{-\infty}^{+\infty} n_\gamma(l)\ n_e(l, ct)\ S(l)\ d(ct)\ dl; \qquad (5)$$

where l is the longitudinal coordinate along the interaction area, $n_\gamma(l)$ and $n_e(l)$ are the volume densities of photons and electrons, $S(l)$ is the beams overlap cross section and ν is the electron photon interaction frequency. $n_\gamma(l)$ depends on the laser system parameters as following:

$$n_\gamma = \frac{P}{\pi\omega_\gamma c r^2(l)}; \qquad r^2(l) = r_o^2\left(1 + \frac{\lambda^2 l^2}{\pi^2 r_o^4}\right) \tag{6}$$

where P is the laser power, c is the speed of light, $r(l)$ describes the laser beam waist radius longitudinal dependence, that is determined by the laser beam focusing system. The $n_e(l)$ we can write as:

$$n_e = \frac{N_e f(l+ct)}{\sigma_x(l)\sigma_z(l)}; \qquad f(x) = \frac{1}{\sqrt{2\pi}\sigma_s} exp\left(-\frac{x^2}{2\sigma_s^2}\right) \tag{7}$$

where N_e is the number of electrons in the beam, $\sigma_x(l)$, $\sigma_z(l)$ are the electron beam transversal sizes and $f(x)$ is the function of longitudinal electron density distribution inside one electron bunch (here we assume that it has gaussian shape).

In the center of the CG cell, that we have chosen for the electron photon interaction area, σ_x=580 μm and $\sigma_z(l)$=87 μm, so the beams overlap cross section for $r(l) >$ 0.5 mm should be mostly determined by the electron beam transversal shape. Now we can finally write for the electron photon luminosity:

$$L = \nu \frac{PN_e}{(\sqrt{2\pi}\sigma_s)(\pi r_o^2)\omega_\gamma c} \int_{-s}^{s}\int_{-\infty}^{+\infty} \frac{exp\left(\dfrac{(l+ct)^2}{2\sigma_s^2}\right)}{1 + \dfrac{\lambda^2 l^2}{\pi^2 r_o^4}} d(ct)\, dl \tag{8}$$

The intensity of the BCS γ-quanta is determined as:

$$\dot{N} = L \cdot \sigma_c(\lambda(\omega_o)) \tag{9}$$

The main contributions to this value are:

- the value of $\frac{p}{c\omega_o}$ that is the longitudinal density of laser photons;
- the dependency of the total BCS cross section from the initial photon energy;
- the dependency from the laser waist size and shape, determined by the focusing optics.

As an example we present the results of calculations for two lines of the Ar laser with:

- ω_o=2.41 eV (green line); P=20 W; r_o=1 mm allows to have $1.4 \cdot 10^7$ photons at 100 mA electron current, that corresponds to 0.66 BCS γ-quanta per one interaction.
- ω_o=3.72 eV (uv line); P=5 W; r_o=0.5 mm allows to have $5.65 \cdot 10^6$ photons at 100 mA electron current, that corresponds to 0.57 BCS γ-quanta per one interaction.

4.3 The Gamma-Beam Spatial Properties

The angular divergencies of the BCS γ–beam are the compositions of the initial angular spreads in the electron beam with the characteristic BCS angle θ_c (eq. 2). We can write them as:

$$\Sigma'_{x,y} = \sqrt{\sigma l_{x,y}^2 + \theta_c^2} \tag{10}$$

where $\sigma l_{x,y}$ are the x, y angular spreads in the electron beam. For the interaction in the center of the CG cell $\Sigma'_x \approx 6.7 \cdot 10^{-5}$, $\Sigma'_y \approx 6.5 \cdot 10^{-5}$. So, at the distance of 20 m from the center of the interaction area the γ-beam transversal size will be about 1.5 mm.

As far as the angular spreads in the electron beam are significantly smaller than the characteristic angle of the BCS process θ_c (see section 3.1), the aperture collimation of the γ–beam at the certain distance from the electron photon interaction point makes the the beam monoenergetic.

This method, however, does not give such high energy resolution as tagging, (see below), and leads to the γ-flux loss. But, it should be mentioned, that it does not require to provide coincidence experiment and, hence, is not limited in the initial γ-flux due to the second limitation, discussed in section 4.2. The first limitation can be also put down by the technique still not implemented anywhere, see [15]. If one generates the BCS γ-beam with the $\omega_{max} \ll \varepsilon$, the scattered electron can stay in the beam after relaxation. Time which needs the electron to return to the equilibrium energy is $\tau_{dump} \approx 5$ ms (for the SPring-8). In this case one can easelly estimate, that the limitation on the γ-flux increases to the $\dot{N} = N_e/\sqrt{\tau\tau_{dump}} \approx 10^{11}\ s^{-1}$. Here τ is the electron beam natural life time, N_e is number of particles in the beam. The only way to reach the monochromatization of such a beam is collimation, because the electrons are not knocked out of the beam at all.

It is not so trivial to estimate ω_{max} because permitted electron energy loss dramatically depend on the peculiarities of the storage ring. One can say that this technique may require rectangular intra laser cavity configuration of the electron photon interaction. The CO_2 laser is the most probable candidacy to be used as a photon source. At the SPring-8 it can provide ω_{max}=60 MeV. Such polarized and monoenergetic γ-beam is the most convenient for the experiments with polarized nuclear targets.

4.4 The Laser-Optical and the Gamma-Beam Monitoring Systems

The laser optical system of the facility consists of the laser head with its power supply, mirrors to transport the laser beam along the optical path, lenses to make a necessary focusing of the beam. The electro-optical (Pockels) cell can be used for the fast changing of the laser light polarization. For controlling the laser parameters several devices should be used: power meters, polarimeters, photo-diode matrixes and TV–cameras for laser beam size and position measurements along the optical path. The aiming system consists the adjustable mirrors, managed by the computer-controlled precise stepping motors.

The monitoring system is used for the on-line measurements of the γ–beam parameters such as: counting rate, spatial distributions and the energy spectrum. It consists of the two-coordinate γ-beam size and shape measurer (proportional or microstrip chamber) and a fast electromagnetic calorimeter to measure the BCS γ-quanta counting rate and the energy spectra. The best aiming criterion to obtain maximum electron photon luminosity provides the feedback from the BCS γ-quanta counting rate, controlled by the γ-quanta monitoring system.

5 Tagging System (TS)

5.1 Main Principles

Tagging of the γ-quantum energy is the most advantage way to get a monoenergetic γ-beam. It gets the highest accuracy in the determination of the γ-quantum energy, and does not lead to the γ-beam flux decrease. Tagging does not strongly depend on the γ-quantum origin, so can be applied as

well to the γ-quanta originating from the bremsstrahlung scattering on the residual gas atoms.

As it was said in section 4.2 tagging means the coincidence between the trigger of the experiment and the tagging system trigger. Main principal of tagging is to measure the final state of the electron after scattering. The scattered electron momentum is analyzed by the deflection in the magnetic field. So, the energy of the γ-quantum ω produced by this electron can be determined from the simple energy conservation as: $\omega = \varepsilon - \varepsilon_e$, where ε_e is the energy of scattered electron.

Scattered electron practically conserves its momentum direction after scattering and stays in the beam until the bending magnet immediately following the interaction point. The field of this magnet is naturally to use as an analyzing field that deflects the electrons with the momenta less than equilibrium. Space sensitive detector, placed beside the bending magnet will give the possibility to determine the electron momentum, and energy. That also fits the requirement set in section 4.1

5.2 Tagging System Parameters

5.2.1 Energy Region

As it was shown in the section 4.1 the best area for the organization of the Compton scattering is in the center of the CG cell. So, the registration device of the TS should be placed after the BD2 (BS2) or BM2 magnet. In the following speculation we recon that the interaction takes place in the center of the direct cell, BD2 is chosen as the analyzing magnet for the TS, the registration system is positioned beside the magnet, close to the next magnetic element (the quadrupole lens QD6, see [17]). As all the lattice functions are the same at the center of any CG cell, all the speculations may be respected to them as well.

Let consider the electron on the equilibrium orbit of the storage ring, that looses fixed energy between BD1 and BD2 magnets. Let also consider, that its momentum direction conserves. In this case all the magnetic structure between the magnets, that has no dipole magnetic fields on the equilibrium trajectory, does not affect the electron's movement. Deflection of the electron after the BD2 does not depends on the point where the electron lost its energy. This deflection versus the value of the lost energy (momentum) is shown in Fig. 4.

Two curves on the plot corresponds to the point at the edge of the magnet (dashed) and at the end of the following straight section about 1 m (solid).

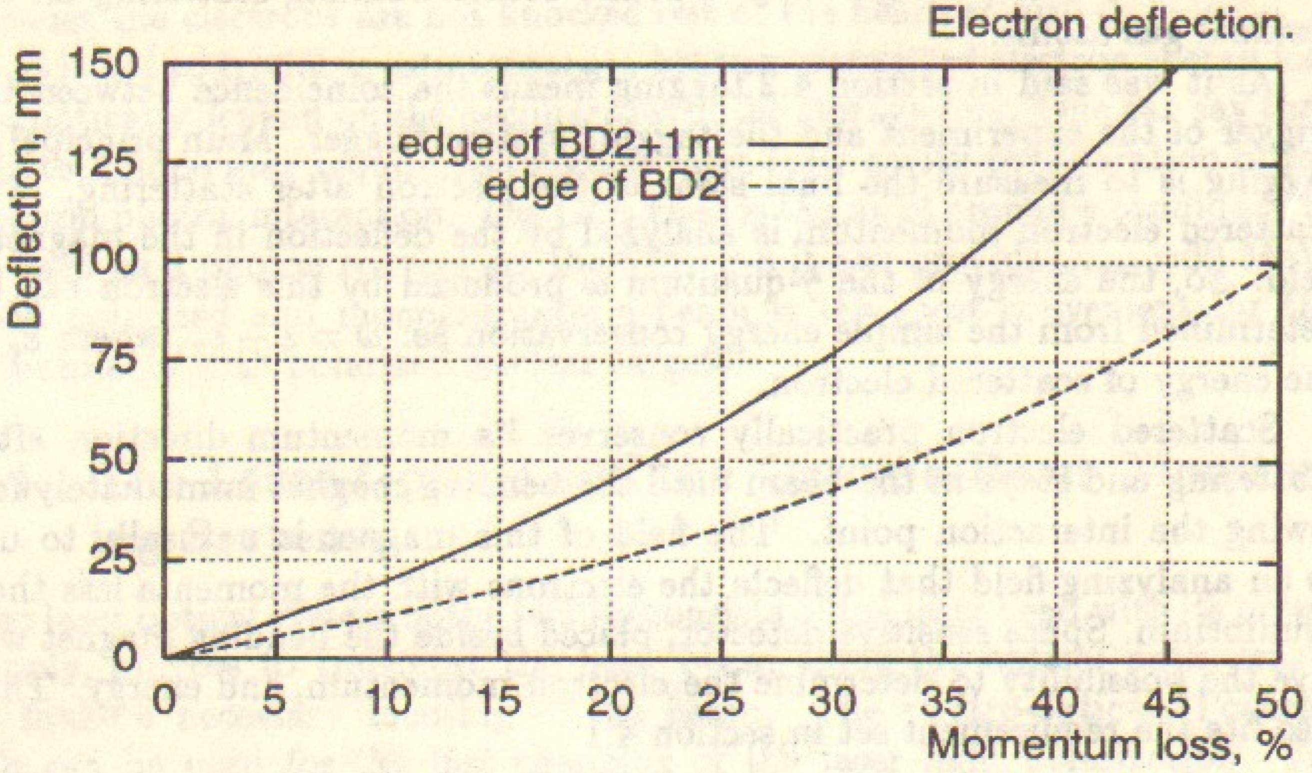

Figure 4: Electron deflection. Dashed line: at the edge of the BD2 magnet; solid line: 1 m from the edge of the BD2 magnet.

As declared in the description of the magnets design (see [17]) the area of the uniform field in horizontal plane is ±30 mm. That means that the electrons with less than 23% momentum loss move in the uniform fields. It is important to note that the scattered electrons from the Compton interaction with 2.41 eV laser photons (main line of the argon laser) have momentum loss up to 22.8%. So, the TS placed here covers the higher edge of the Compton spectrum. Moreover, a simple estimation shows that the electrons with even 80% lost momentum do not meet the aperture limitation raised from the magnet yoke (about 300 mm at the edge of the magnet). Calculation of the trajectories for such electrons requires the accurate knowledge of the magnet design. In the present Proposal all the calculations were done for the electrons with less than 50% momentum loss. This value covers any Compton energy for electrons scattered by laser of visible and close UV light region.

The limitation in the registration of the electrons with the low momentum loss rises from the electron beam dynamic aperture. Such electrons are not significantly deflected by the magnet and their trajectories lie close to the equilibrium orbit. It is clear that any registration device which one can use for the TS, put close to the circulating electron beam destroys it. It is difficult to calculate the exact distance, where the aperture will not affect the beam, but simple estimations may give quite an accurate knowledge about this parameter.

For the estimation let consider that the aperture limitation situated at the distance $10 \cdot \sigma_x$ does not cut the tails of the electron beam distribution, so it does not decrease the electron beam life time. At the point where the TS registration system may be maintained $\sigma_x = 214\mu m$. Thus the admitted aperture limitation is 2.14 mm, that corresponds to 1.2% of the electron momentum loss.

Summarizing these estimation one can say, that the γ-quantum energy region of TS may be from about of 1.2% ($\approx$ 100 MeV) up to about 80% ($\approx$ 6400 MeV). In this Proposal we calculated all the data from 5% up to 50% for the electron momentum loss.

5.2.2 Energy Resolution for Zero Gamma-Quanta Energies

Energy resolution of the TS is σ_γ for the zero γ-quanta energies can be easely estimated as:

$$\sigma_\gamma = \sqrt{\left(\sigma_x \Big/ \frac{dx}{d\varepsilon}\right)^2 + \sigma_e^2} \qquad (11)$$

where σ_e is the energy spread in the electron beam (8.75 MeV), $\sigma_x = 214\mu m$, $\frac{dx}{dE}$ is the derivate from the curve, shown in Fig. 4. Calculated by this formulae σ_γ equals 12.4 MeV at near zero electron momentum loss. In the following section we will extend this estimation for any energy of γ-quanta.

5.2.3 Method of Calculation

In order to calculate the energy resolution of the TS we used the same technique as in [16]. This technique possesses not to carry out Monte-Carlo simulation, but by mean of standard codes, applyed for the accelerator design, calculate the parameters of the TS. For the present calculations we used the MAD program available from CERN [18].

Independent factors contributing the TS energy resolution are:

i. Energy spread in the electron beam.

ii. Spread of the scattered electrons along the X-coordinate on the TS registration system surface.

iii. Spatial resolution of the TS registration system.

Item i. is a constant declared in the [17] and consists 8.75 MeV. Item iii. will be discussed below, but the TS registrator may be build is such a way that its spatial resolution will not affect the total energy resolution. So, only item ii. is the matter of discussion.

Idea of the method is based on the fact that one can exclude factor of time from the consideration. That means, that there is no difference if the scattered electrons enter the TS registrator from many revolution of the beam or simultaneously. Of course, this approach is true if the scattered electrons do not interact each other or the equilibrium electron beam. This admission is fulfilled. In this case one can define the "scattered electron beam" (SE-beam) and deal with it instead of tracking each scattered electron. Spread of the scattered electrons at any point is the same as the SE-beam size.

It is also necessary to set the framework where the SE-beam is valid to use for calculations. The energy of scattered electron is not fixed, so we introduce the SE-beam for each energy separately. Initial bounding conditions for the SE-beam should be taken from the equilibrium electron beam in the point of electron photon interaction. All the alpha, beta and dispersion functions as well as the position of the electron beam may be carried onto the SE-beam immediately after interaction. We must also take into account that the emittance of the electron beam is transformed in the scattering. Transformation of the emittance will be discussed in the next paragraph. In our calculations we consider that the equilibrium electron beam follows the zero orbit (zero means that the orbit lies on the centers of magnetic elements). In this case the trajectory of the SE-beam will coincide with the equilibrium before the nearest dipole magnetic element. Final point of the trajectory until which the consideration of the SE-beam is valid, is the point where the SE-beam exits the uniform fields of the magnetic elements along the X-coordinate.

As it was said the emittance of the SE-beam is different from the emittance of the equilibrium electron beam. Emittance $\epsilon = x' \cdot x$, where x is the transverse beam size, and x' is the transverse angular dispersion in each point of the beam. Parameter x conserves in the interaction, while x' increases. For the Compton interaction the average by spectrum angle that gets the scattered electron after interaction is:

$$< x' >= \frac{15\pi}{2^7} \cdot \frac{\lambda}{\gamma}, \tag{12}$$

where λ is defined in formulae (1), $\gamma = \frac{\varepsilon}{m}$. This value is 6.95 μrad, while the $x' = \sqrt{\epsilon/\beta}$ at this point is 16.5 μrad, β is the horizontal beta-function at this point. Even the maximal angle that gets the electron in the Compton scattering:

$$< x' >= \frac{1}{2\gamma} \cdot \frac{\lambda}{\sqrt{2+\lambda}} \quad \textit{at the energy} \quad \varepsilon_e = \frac{2}{2+\lambda} \cdot \varepsilon \tag{13}$$

is only 10.7 μrad that is less than 16.5 μrad. In our calculations we neglect the emittance increase in the Compton scattering. It is important to note that in the bremsstrahlung process the transverse angle that gets the electron after scattering is bigger and may overcome x'.

So, the calculations were provided as following. For the fixed energy we traced the SE-beam through the part of the SPring-8 magnetic structure from the interaction point to the point where the TS registrator should be installed. All the parameters of the magnetic elements were recalculated for the certain energy, and the SE-beam size gotten at the exit of the section corresponds to the spatial dispersion of the scattered electrons.

5.2.4 Results of Calculation

Calculated value of the SE-beam size at the position of the TS registrator is shown in Fig. 5. The long dashed curve takes into account the transformation of the beta function only. The second contribution to the SE-beam size gives the dispersion function, which equals to zero at the equilibrium energy, but increases with the electron momentum loss (short dashed line). Square sum of both contributions is shown with solid line.

5.3 Background Conditions

As it was mentioned in the item [iii.] of the section 4.1, the interaction area should be placed in the short straight section in order to have less bremsstrahlung γ-quanta flux coming from it. This requirement is important not only from the point of view of the polarization quality of the γ-beam, which are not discussed in this section, but from the point of view of the TS resolution also.

In the Fig. 6 is shown the energy resolution of the TS. Energy resolution for the scattered electrons is the dashed line, for the γ-quanta is solid. The second takes into account the energy spread in the electron beam. This addition is necessary to include, because the γ-energy is calculated as $\omega = \varepsilon - \varepsilon_e$.

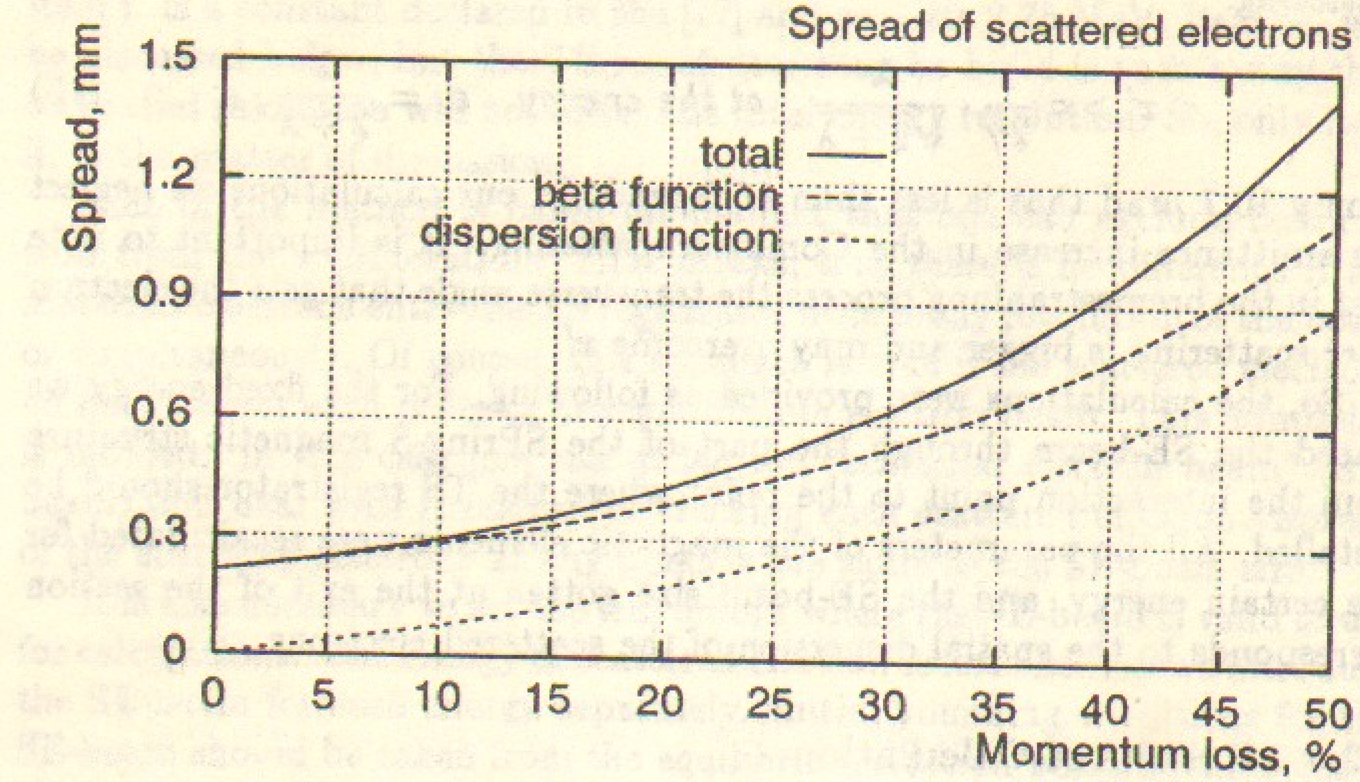

Figure 5: Spread of the scattered electrons. Dashed line is calculated by the beta functions, points by the dispersion function, solid line is the full size.

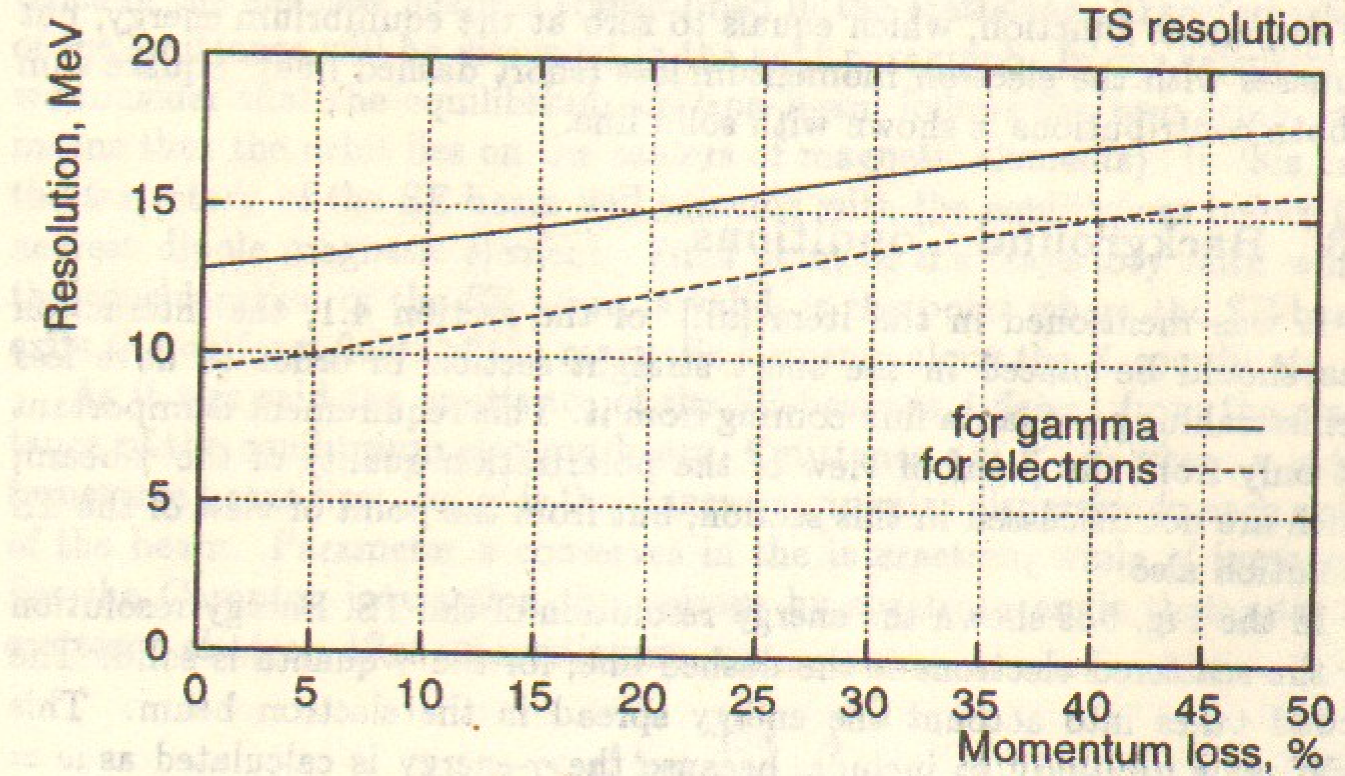

Figure 6: Energy resolution of the TS. Dashed line is for electrons, solid line is for γ-quanta.

In fact, the tagging, as the method to make monoenergetic γ-beam, is not sensitive to the process how this beam is produced. Scattered by the residual gas atom, the electron also comes on the TS registrator, and its momentum is measured. But two differences from the Compton scattering should be pointed out. The first one is that the area of the bremsstrahlung scattering is as long as the length of the section, so the part of the magnetic structure of the storage ring, that passes the scattered electron, before it enters the TS registrator, may be different. The second is that the angle of scattering in the bremsstrahlung process for the electron is bigger than in the Compton process.

In the Proposal we did not follow the aim to get the precise data of the TS resolution for the bremsstrahlung γ-quanta, but some estimations are given. In Fig. 7 is shown how the TS energy resolution versus energy depends on the point of the scattered electron emission. The straight section of the SPring-8 is divided into 5 intervals by the quadrupoles as they stay in the section of the SPring-8, see [17]. One can see that the resolution dramatically decreases than the electron scatters before the focusing quadrupoles QF5.

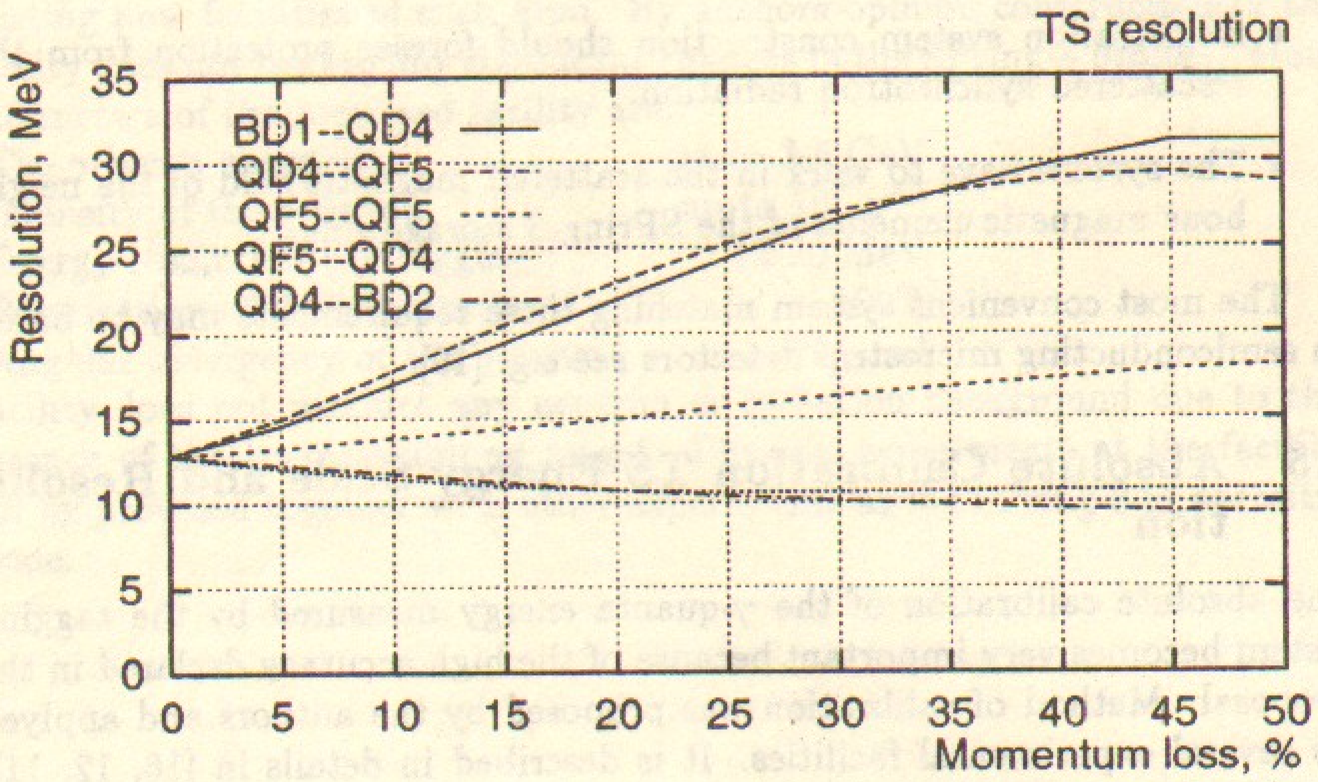

Figure 7: Behavior of the TS energy resolution depending on the scattered electron emission point. The lower curves are close to the analyzing magnet. Curve in the middle corresponds to the emission from the center (basic case).

It is also necessary to note that than the electron loses significant part of its momentum, the angle of scattering plays role. The resolution will be worse than shown in Fig. 7. It can be calculated accurately, considering that the vacuum conditions along the straight section are constant.

5.4 The Registration Part of the TS

The registration part of the TS have to satisfy the following requirements:

- The coordinate resolution should correspond to the SE-beam size as shown in Fig. 5, which at the extremum is of about 200 μm ($2\sigma_x$).
- Counting rate per one channel should be 10^5 s^{-1}.
- To provide energy resolution of the TS in the whole energy range, number of registration channels should be about 300.
- Registration system construction should permit to move it in the horizontal plane in order to position the system as close as possible to the dynamic aperture of the equilibrium electron beam.
- Registration system construction should foresee protection from the rescattered synchrotron radiation.
- The system have to work in the scattered magnetic field of the neighbour magnetic elements of the SPring-8 storage ring.

The most convenient system matching these requirements may be based on semiconducting microstrip detectors see e.g. [19].

5.5 Absolute Calibration TS Energy Scale and Resolution

The absolute calibration of the γ-quanta energy measured by the tagging system becomes very important because of the high accuracy declared in the Proposal. Method of calibration was proposed by the authors and applyed for several experimental facilities. It is described in details in [16, 12, 11]. Main idea of the method is to use natural property of the Compton spectrum, its sharp upper edge. Energy of the edge depends on the well known parameters as the energy of the laser photon, the energy of the electron beam, and electron photon meeting angle. Position of the spectrum edge on the scale of the TS gives the energy point with the accuracy better than the energy resolution. As the TS scale is not linear, see Fig. 4, a set of the laser wavelengths is needed. That can be easely achieved by using several wavelengths of the Ar laser, or several different lasers. It should be note that the γ-flux for calibration may be several order lower than for the experiment. Another way is to change the meeting angle between electron and laser beams while the laser photon energy is fixed. This approach, however, strongly depends on the real conditions.

Another advantage of the method is that not only the absolute energy scale of the TS, but its energy resolution as well, can be experimentally measured. As shown in [16] the spread of the upper spectrum edge, measured by the TS, depends only on the energy resolution of the TS. Analyzing the shape of the spectrum edge restored by the TS one can define the energy resolution of the system.

6 Conclusion

In the Proposal is shown the possibility to build the BCS facility at the SPring-8 storage ring. The facility will have the best parameters of all the existing now facilities of such kind. By authors opinion construction of the facility does not lead to any significant changes in the SPring-8 project. Main parameters of the proposed facility are:

The γ-beam energies:	up to 3.4 GeV
Intensity of the γ-beam:	up to 10^7 s^{-1}
Energy resolution (by tagging):	13-20 MeV
Polarization of the γ-beam:	100%
Angular divergency of the γ-beam:	≈ 70 μrad

Facility does not produce any neutron or radiation background due to the absence of the bremsstrahlung target. Physical experiments at the facility can by provided together with other experiments at the SPring-8 in parasitic mode.

A APPENDIX: Refinement of the TS resolution by the SE angles measurement

A.1 Main idea

Main idea is to take into account energy deviation of the electron before scattering from the equilibrium energy of the electron beam ε. Value of this deviation can be restored after scattering, if the angle of the electron at the registrator is measured. Let us point out three main peculiarities of the project, which are the keystones for the further speculations. They are:

1. The electron-photon interaction area is organized at the place, where the dispersion function of the SPring-8 reaches maximum.
2. Angular spread at this point is minimal.
3. Compton scattering does not affect the angular spread in the SE-beam.

By the other words item 1. means that in the electron beam at the point of the electron-photon scattering in the X-plane exists the energy gradient. Electron coordinate can be written as:

$$x = x_\beta + \eta \Delta\varepsilon, \tag{14}$$

where x_β is the electron coordinate due to the betatron oscillation, η is the value of the dispersion function, $\Delta\varepsilon$ is the deviation of the electron from the equilibrium energy ε. Now we can introduce the transport matrix of the rank 3 for the X-plane:

$$\begin{bmatrix} x \\ x' \\ \Delta\varepsilon \end{bmatrix}_1 = \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ x' \\ \Delta\varepsilon \end{bmatrix}_0 , \tag{15}$$

where index "0" corresponds to the parameters of electron photon interaction point, index "1" to the azimuth of the TS registrator. Substituting eq. 14 into the formulae. 15 one can write for the angle:

$$x'_1 = d\,x_\beta + e x'_0 + (\eta\, d + f)\Delta\varepsilon, \tag{16}$$

It should be note that equation like 14 may be written for the x' too: $x' = x'_\beta + \eta'\,\Delta\varepsilon$. However the contribution of the second term is negligible in our case due to the factors enumerated above.

Solution of the eq. 16 shows that the value of $\Delta\varepsilon$ can be obtained than the angle x' is measured. Two other contributions from x_β and x'_0 can be taken equal to their average value, i.e. equal to zero. Discussed parameters are shown in the scheme in Fig. 8.

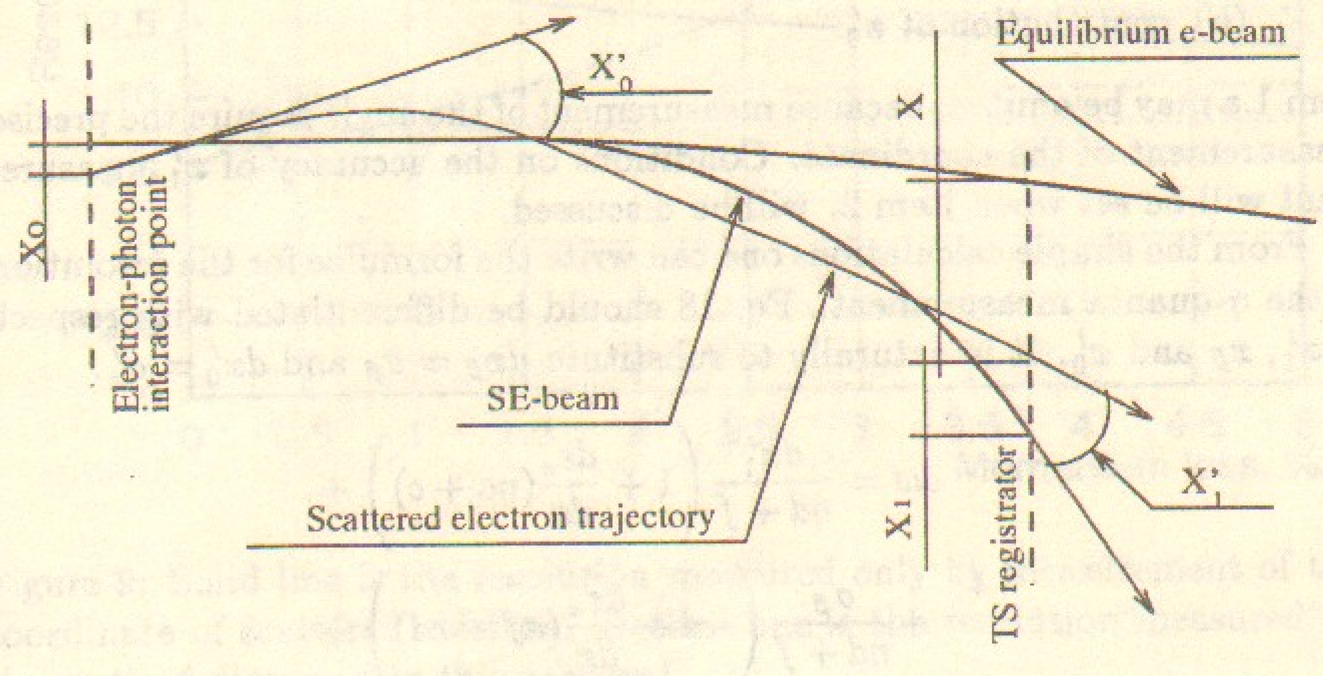

Figure 8: Schematical view of the scattered electron trajectory.

Now we can make correction to the energy of γ-quantum ω measured by coordinate of the associated electron.

$$\omega = \varepsilon - \varepsilon_e(x) \tag{17}$$

where ε is the energy of the electron beam and $\varepsilon_e(x)$ is the energy of the scattered electron, measured by the coordinate. Both terms in the eq.17 should be corrected. $\varepsilon \longrightarrow \varepsilon + \Delta\varepsilon$ and $\varepsilon_e(x) \longrightarrow \varepsilon_e(x - x_1)$, where x_1 can be obtained from the first line of the formulae 15 substituting in it the value of $\Delta\varepsilon$.

$$\omega = \varepsilon - \varepsilon_e(x) + \Delta\varepsilon + \frac{d\varepsilon_e}{dx} x_1 \tag{18}$$

A.2 Accuracy

Resolution of the method depends on four factors which are united into two parts:

1. Measurable parameters:

   (a) accuracy of x measurement,
   (b) accuracy of x'_1 measurement;

2. Immeasurable parameters:
   (a) contribution of x_β,
   (b) contribution of x'_0.

Item 1.a may be omited, because measurement of the angle require the precise measurement of the coordinate. Conditions on the accuracy of x'_1 measurement will be set when item 2. will be discussed.

From the simple calculations one can write the formulae for the resolution of the γ-quanta measurement. Eq. 18 should be differentiated with respect to x'_1, x_β and x'_0. It is naturally to substitute $dx_\beta = \sigma_\beta$ and $dx'_0 = \sigma'_x$.

$$\begin{aligned} d\omega = {} & \frac{dx'_1}{\eta d + f}\left(1 + \frac{d\varepsilon_e}{dx}(\eta a + c)\right) + \\ & + \frac{\sigma_\beta}{\eta d + f}\left(-d + \frac{d\varepsilon_e}{dx}(af - cd)\right) + \\ & + \sigma'_x\left(b\frac{d\varepsilon_e}{dx} - \frac{e}{\eta d + f}\left(1 + \frac{d\varepsilon_e}{dx}(\eta a + c)\right)\right) \end{aligned} \tag{19}$$

As one can see the second and the third addenda in the eq. 19 correspond to the items 2.(a and b).

A.3 Calculations

As it is clear from the eq. 19 factor $\eta d + f$ should be made as big as possible. In real conditions of SPring-8 it is extremely small. That is the reason why this technique is impossible to apply at the place where the TS registrator is situated (see 4.1). The best place, that was chosen, is the position of QF5 quadrupol, following the second bending magnet after the electron-photon interaction area. It is considered that the interaction takes place in the direct Chasman Green cell, and the second bending magnet is situated in the following mirror symmetrical cell. Direct means that the order of elements is the same as in [17]. In this case factor $\eta d + f$ is about 0.12 (units of MAD code [18]). Unfortunately at this place coefficients b and e are big but has the same sign, so are partialy subtracted as seen from eq. 19. Resolution for this place is shown in Fig. 9. Energy spread in the electron beam consists 8.75 MeV as mentioned in [17]. Accuracy of angle measurements, which does not affect the final resolution is of about (15-25) μrad. Contributions of factors mentioned in items 2.a and 2.b are shown in Fig. 10. One can see that the contribution of angle dispersion at the interaction point is much bigger.

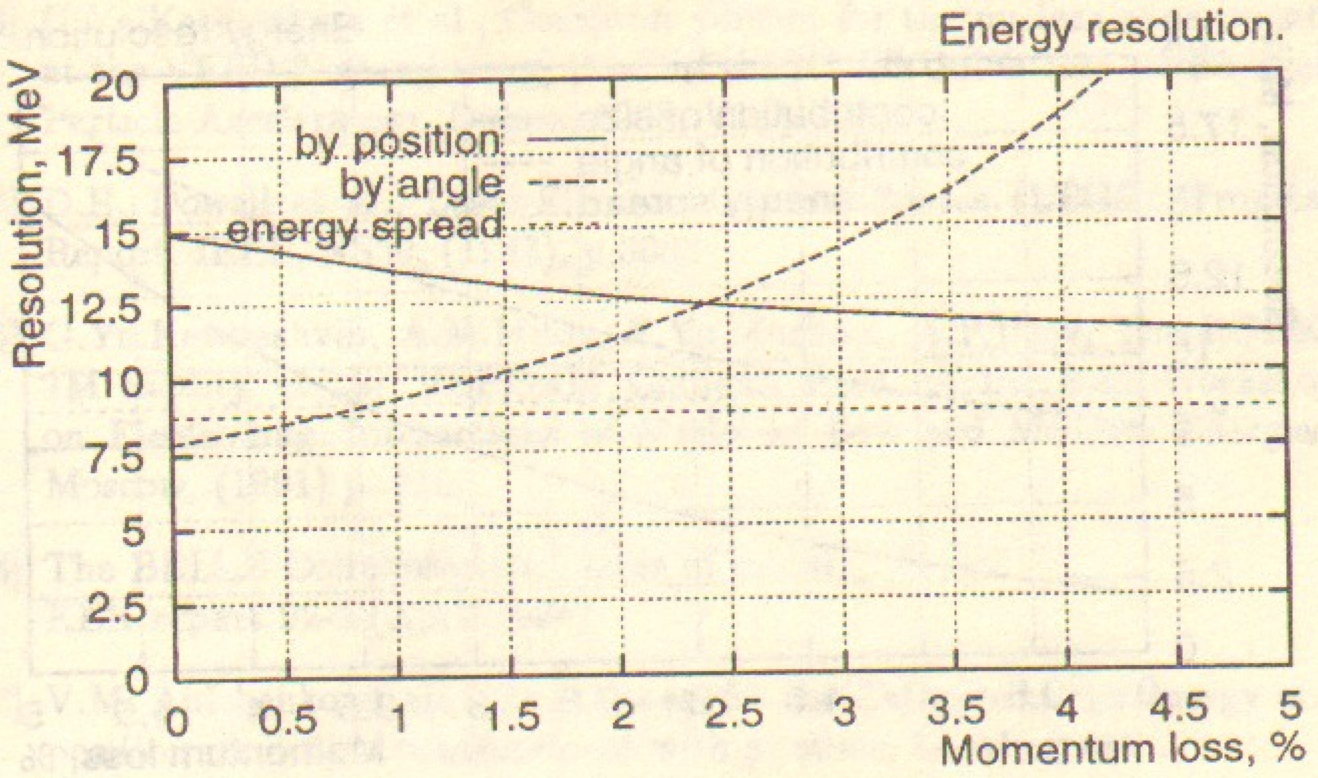

Figure 9: Solid line is the resolution measured only by measurement of the coordinate of scattered electron. Dashed line is the resolution measured by the method discussed in this proposal.

A.4 Conclusions

In the appendix the principal possibility to tag the energy of γ-quanta with the resolution better than the energy spread in the electron beam is shown. Realization of this method requires adjustment of the SPring-8 storage ring structure to make parameter $\eta d + f$ bigger, what can improve resolution in wider range of the γ-quanta energy and make requirement on angle measurement softer.

Application of the method may give possibility to build the tagging system with the extremely high resolution of 3-5% in the energy region, where by common methodics the TS cannot give resolution appropriate to the utilization in the wide range of experiments.

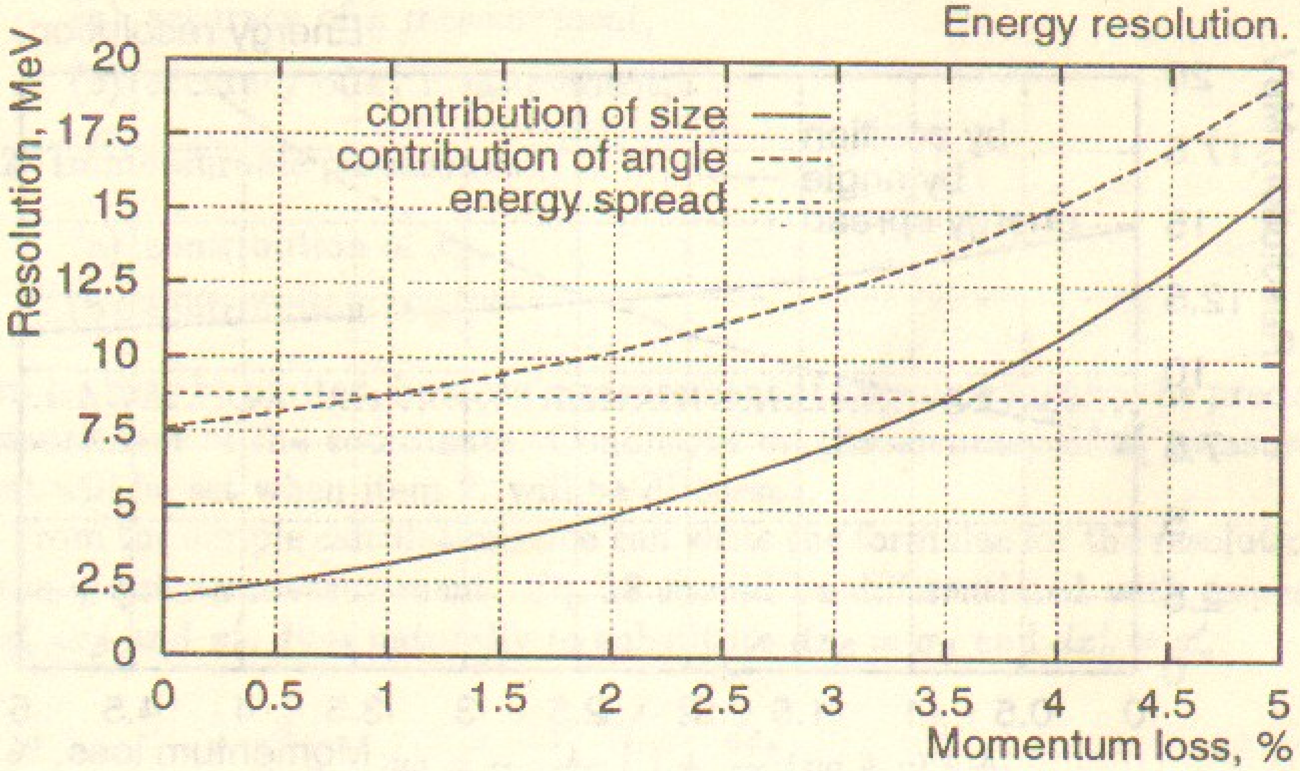

Figure 10: Solid line is the contribution in the resolution from the betatron size of the beam at the interaction point. Dashed line is the contribution from the angular spread of the beam at the same point.

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Budker INP 95-79

Г.Я. Кезерашвили, А.М. Милов, Н.Ю. Мучной

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