

# ON THE DISCOVERY OF COHERENT BREMSSTRAHLUNG IN A SINGLE CRYSTAL AT THE FRASCATI NATIONAL LABORATORIES

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Since the end of 1950s the Frascati National Laboratories have started intense research program devoted to studying the coherent phenomena of relativistic electron interactions in crystals. First results were impressive: Frascati's Spectrometer has first detected coherent radiation by electrons in crystals, i.e. coherent bremsstrahlung. The discovery not only proved the Ferretti-Uberall prediction, but also has corrected the theory of coherent bremsstrahlung. Carrying out intensive studies on coherent radiation phenomena in crystals a number of innovative techniques to measure fine features of radiation, such as polarization measurements, was developed. The Frascati's group was even close for the first time to observe channeling radiation discovered about two decades later the pioneering work on coherent bremsstrahlung.

## 1. Introduction

The propagation of electron beams through the solids leads to the emission of radiation known as "bremsstrahlung"<sup>1</sup>; interacting with the Coulomb field of target nuclei, the electrons will be deflected ("braked"), as a result, emitting continuous electromagnetic radiation (sometimes in literature mentioned as "incoherent bremsstrahlung"). Some fine features of the radiation can be distinguished in the case of periodic target structure; thus, in case of the crystal target this type of radiation becomes incontinuous, with several resonances (peaks), and can be both monochromatic and polarized.

The behaviour of electron crossing a crystal has been studied since very long time. The one of the first theoretical paper on this subject quoted in many successive papers as well as in the first report of the Frascati's group on coherent radiation of electrons in crystals, is the Bethe paper "Theorie der Beugung von Elektronen an Kristallen" published in 1928 [1]. In 1950 Ferretti predicted the coherent bremsstrahlung (CB) emission by electron interacting with periodic crystal potential [2]. The coherent emission was predicted in that paper in

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<sup>1</sup> German term for "braking radiation", first introduced by Sommerfeld.

qualitative way, calculating the electron scattering by virtual photons of a periodic potential (the Weiszacker-Williams method). However, only in 1956 Uberall published the first theoretical results that could be compared with experimental data [3] (see, also the proceedings of “Channeling 2004” [4]).

Successfully the group of Diambri has started the experimental studies on CB at the Frascati 1 GeV electron synchrotron (see, his report to the “Channeling 2004” [4]). The main purpose of the research was to verify the expected CB emission by means of the group’s pair spectrometer. The results obtained in the routine work campaign, have partially confirmed the Uberall’s prediction on the existence of coherent emission by relativistic electrons traversing the crystal targets.

But the most important discovery was the fact that new very important features have been observed. Unexpected quasi-monochromatic photon line emission was detected; it was becoming very sharply defined in particular for the diamond crystal. The analysis had clarified the limits of the Uberall approximation, and based on experimental data, a new computation were soon performed.

It is notable that at the time of the Frascati’s experiment the channeling radiation was unknown, and only later on, more than 20 years distance, a unifying theory for both channeling radiation and CB was developed. However, the Frascati’s team was the first measured a relevant increase of low energy photon emission when the electron initial momentum is collinear with the crystal main axis.

## 2. The Pair Spectrometer

The Electron Synchrotron was the first high-energy accelerator realized in Italy. The project for electron synchrotron was approved in 1953 and its construction as a new laboratory has started in 1957 in Frascati, small town situated in a few kilometers south of Rome. After two years the accelerator began operational, delivering to the users the photon beams with energy between 0.4 and 1.1 GeV, obtained by hitting the electron beam against a target inside the synchrotron vacuum vessel. The  $\sim 9$  m diameter ring consisted of 4 weak-focusing bending magnets separated by 4 short straight sections (S.S). From one of the S.S at the end of the acceleration cycle the electron beam, impinging on an internal tungsten target, have generated a bremsstrahlung beam. Successfully, the registered spectrum has analyzed by an electron positron pair spectrometer (PS) as shown in Fig. 1 .

PS was built as a general facility of the Frascati electrosynchrotron and played a substantial role in studying the high-energy electrodynamic processes in crystals. The first experiment dedicated to coherent pair production in a crystal was realized inserting a thin silicon target inside PS mounted on a goniometer. The results of this experiment are shown in Fig. 2.

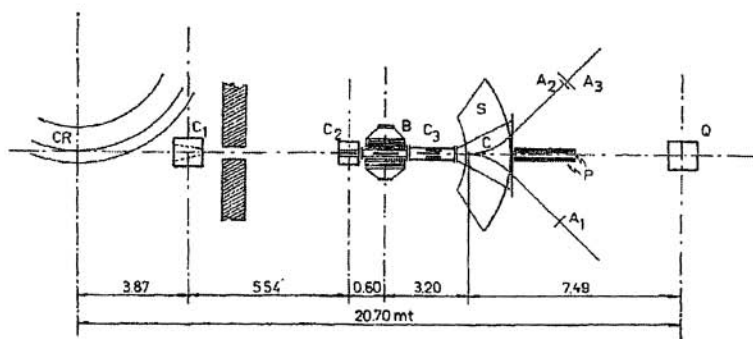


Figure 1. The Frascati Electron Synchrotron Pair Spectrometer

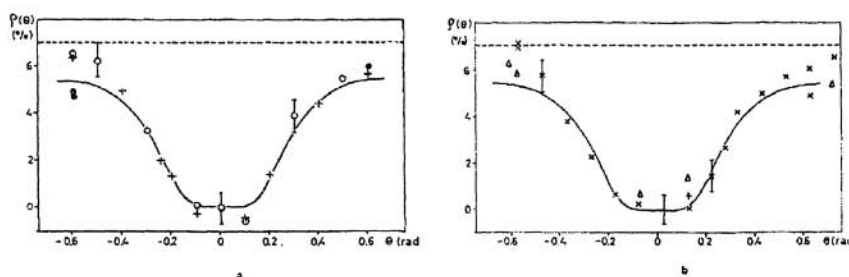
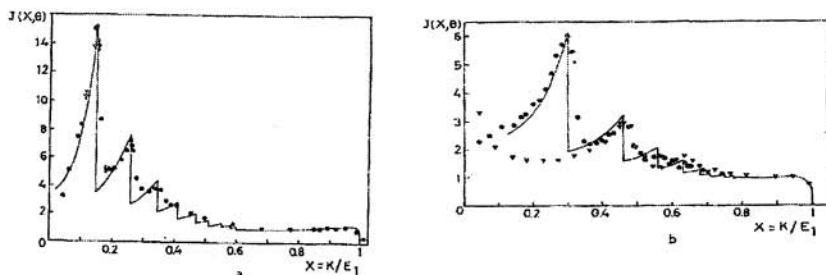


Figure 2. Relative variation of the electron pair production cross section in a Si single crystal versus  $\theta$  (angle between  $\gamma$ -ray direction and the crystal axis [100]). The solid line represents the theoretical curve obtained within the first Uberall approximation. The central energy of the incident photon is  $K=910$  MeV. The experimental points are represented by the various shape dots. Different runs of measurements are related to different shapes of the dots. Parts (a) and (b) refer to rotations of the crystal about the horizontal and vertical axis, respectively.

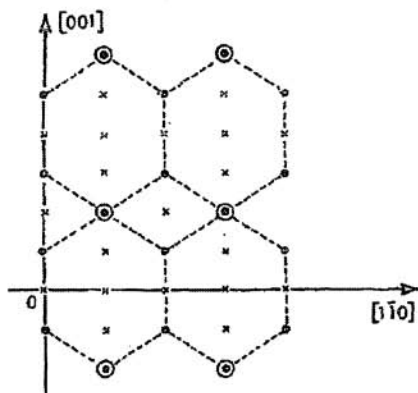
### 3. Coherent Bremsstrahlung from a Diamond Crystal

After the success of the experimental studies on the coherent pair production in Si crystal [5], when Barbiellini joined the activity as a PhD student, the Frascati group has started the ambitious project "Coherent Bremsstrahlung" inserting a crystal mounted on a high precision goniometer, projected by Guido di Stefano, into the electron synchrotron vacuum chamber. In the first run of the experiment silicon crystal was used providing with positive results, but soon after, as the outcome of an accurate search for the best crystal to maximize the coherent emission in the continuum, a diamond crystal with the axis  $\langle 110 \rangle$  almost parallel to the beam was mounted in the high precision goniometer.

The experimental results obtained in that run are shown in Fig. 3; they clearly demonstrated for the first time the possibility for creating a quasi-monochromatic high-energy photon beam.



**Figure 3.** (a) CB intensity for  $E_0=1$  GeV electrons in a diamond crystal. The incident momentum lies in the plane  $[110][\bar{1}10]$  and makes the angle  $\theta = \theta_1 = 4.6 \pm 0.1$  mrad with the axis  $[110]$ . Solid line is the theoretical curve without any correction. (b) The same situation as in (a), but  $\theta = 11.3 \pm 0.1$  mrad for the dots and solid line, and  $\theta = \theta_2 = 22.9 \pm 0.1$  for the triangles.



**Figure 4.** The reciprocal lattice plane through  $h_1=1$  for the diamond crystal (see text).

The bremsstrahlung spectra shown in Fig. 3 are obtained changing the angle  $\vartheta$  between the primary electron beam and the diamond crystal axis, namely the  $\langle 110 \rangle$  axis. The physical origin of the intensity peaks becomes evident if to look at the scheme of Fig. 4 showing the reciprocal lattice structure in the  $[002][\bar{1}10]$  plane as well as the intersection of the region of possible nucleus recoil during the photon emission. While at the incoherent bremsstrahlung process all the recoils of the pancake region are allowed, CB can be realized only for discrete

values of the recoil vector ( $\mathbf{q}$  in the figure) that coincide with a point of crystal reciprocal lattice<sup>2</sup>.

The pancake region defined by two surfaces separated by the value of the longitudinal recoil momentum  $\delta$ , is displaced from the reciprocal lattice origin by the same quantity (Fig. 5). If the angle  $\vartheta$  is zero, CB is not allowed; the electron oscillates interacting with the atomic row as a whole and channeling radiation is emitted (at the time of the Frascati experiments the channeling phenomenon was unknown!). The spectra shown there are obtained for different  $\vartheta$  values corresponding to different reciprocal lattice points entering in the pancake with longitudinal recoil momentum very close to  $\delta$ .

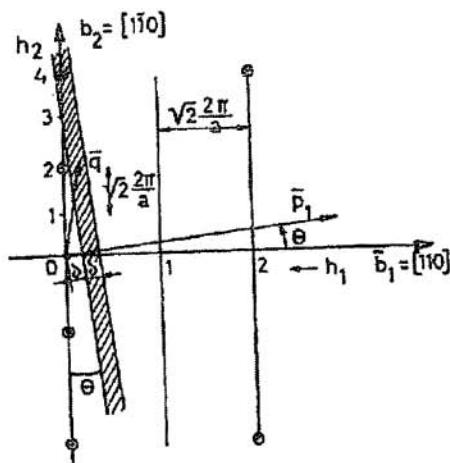


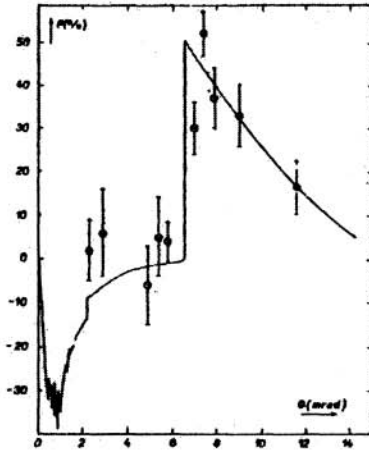
Figure 5. Explanation of CB origin in reciprocal crystal plane [6].

Linearly polarized photons mostly produce electron-positron pairs in the plane of polarization. This fact was used in a set of experiments performed by Barbiellini et al [7]; indeed, the CB polarization was first measured in Frascati for 1 GeV electrons in diamond crystal (Fig. 6). The group measured symmetrical electron-positron production yields for 150 MeV photons in  $\sim 10 \mu$  aluminum radiator. The measurement method was beam-energy limited because of the small angles in pair production. The procedure first applied for the energies less than 0.5 GeV later on was extended for the energy range up to 1 GeV.

Successfully, the method for measuring linear radiation polarization at energies above 1 GeV was developed using coherent electron-positron pair

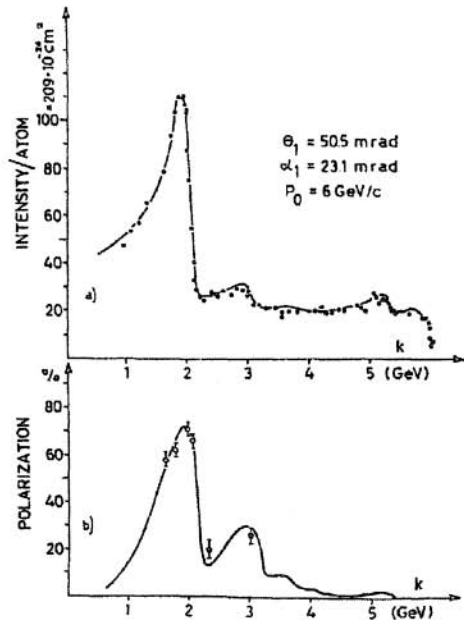
<sup>2</sup> Barbiellini was the first explained the discrete-peaks coherent emission as due to the crystal structure.

production in thin targets and the correlation between the polarization and reciprocal lattice vectors [8].



**Figure 6.** Linear photon polarization as a function of the angle  $\theta$  between the electron momentum and the diamond-crystal axis (first CB polarization measurements; Frascati's experiment). The solid curve represents the theoretical predictions.

**Figure 7.** Measurement of the polarization of CB by the analyzing crystal method. (a) "One-point" spectrum obtained with  $\theta=50.5$  mrad,  $\alpha=23.1$  mrad,  $E_0=6$  GeV. (b) Results of the polarization measurements along the former spectrum. (DESY experiment).



The pioneering work carried out at the Frascati Electron Synchrotron was soon followed by the research at the existing electron accelerator and later on at higher energy machines. In many laboratories, operating with relativistic electron

beams, the predicted CB spectra were computed for higher energy values of the primary electron beam. In Fig. 7, for example, the predictions for CB and its degree of polarization in comparison to experimental results obtained at the DESY electron synchrotron in Hamburg (Germany) are shown [9]. It is clearly seen the progress in CB measurements.

#### 4. First hint of channeling radiation at LNF

The alignment of the beam from electron bremsstrahlung in the diamond crystal was an experimental procedure done at the beginning of every new run. The image of the beam crossing three collimators  $C_{\{1,2,3\}}$  (see Fig. 1) was recorded by a Polaroid film fixed in front of the Wilson Quantameter Q. The beam spot was maximized by moving the collimators, the exposure was done at the fixed electron number on the crystal target. Several of many alignment procedures resulted in a clear over-exposure of the image on the Polaroid film.

In order to define a possible correlation of the image over-exposure with some of the beam parameters, Gian Paolo Murtagh was studying this phenomenon. After a long search for the possible source of the over-exposure it was found that the effect is observed every time when the angle between the electron beam and the crystal axis was equal to zero as remained after the previous working run. The correlation was confirmed by many film exposures at the same experimental conditions. The possibility that very soft radiation emission could be coherently stimulated when the electron is crossing the crystal periodic potential at zero angle became clear but within the framework of the coherent interactions in crystals. However, the forward (zero angle) emission was measured by means of one emulsion instead of the main instrument, namely, the Pair Spectrometer. The emulsion was used for a usual procedure of the alignments of the  $\gamma$ -beam with collimators of the pair spectrometer etc, and very bright spots due to soft photons were recorded. The explanation of the observed over-exposure at zero angles with respect to the main crystallographic axis can be considered as a first experimental hint of the existence of channeling radiation.

The experimental efforts defined a line for both the deeper investigation on a new discovery of the monochromatic and polarized photon production due to CB and the polarization measurements. The lower sensitivity of the spectrometer was 70-100 MeV that was too high for efficient studying channeling radiation spectra for 910 MeV electrons crossing diamond crystals [11].

#### Conclusion

Coherent bremsstrahlung is a subject with a long history, the earlier parts of which are covered in a number of devoted works published by Diambri Palazzi, Uberall, Timm, Ter-Mikaelian, Akhieser and many others. By theoretical and experimental results obtained as well as by new technical solutions proposed during the CB studies the period of 50s and 60s of the last century can be characterized as a revolution in radiation physics, in physics of

novel powerful radiation sources. However, it is interesting to underline that all the studies were carried out keeping the incident beam direction far away from the main crystallographic directions. Another point to be mentioned is the increase of coherently emitted radiation power with the increase of incident beam energy; due to that fact, successful research were performed for higher energy beams. The reason for that was very simple: first, the approximations used are valid only for high-energy beams traversing the crystal target under the angles distant from the main crystallographic directions<sup>3</sup>; and, second, “unpleasant” long penetration features of the incident beams at small angles between the beam and the crystallographic axis or plane (the last results in high beam flux, which may be accompanied by intense channeling radiation).

The history of successful experimental investigations of the features of CB started at the Frascati Electron Synchrotron. Very precise planned measurements allowed the crystal-lattice structure influence on radiation spectrum emitted by the 1-GeV electron beam in a diamond crystal to be first recorded; moreover, theoretical explanation of the effect was also proposed and successfully developed. Starting from that famous works, the experiments on CB studies were continued in many other world centres, such as SLAC, CERN, DESY, Cornell CEA, Kharkov PhTI, Tomsk NPhI, Yerevan PhI, giving light for new discoveries in the physics of relativistic beams interaction with the crystalline targets.

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<sup>3</sup> The approximation used is the 1<sup>st</sup> Born approximation, which is also valid for the electron incident angles close to the main crystallographic directions but for lower electron energies; however, it was shown much later [10].