ADVANCED PHOTON SOURCES AND THEIR APPLICATIONS

JLab Oct 29

R. Avakian

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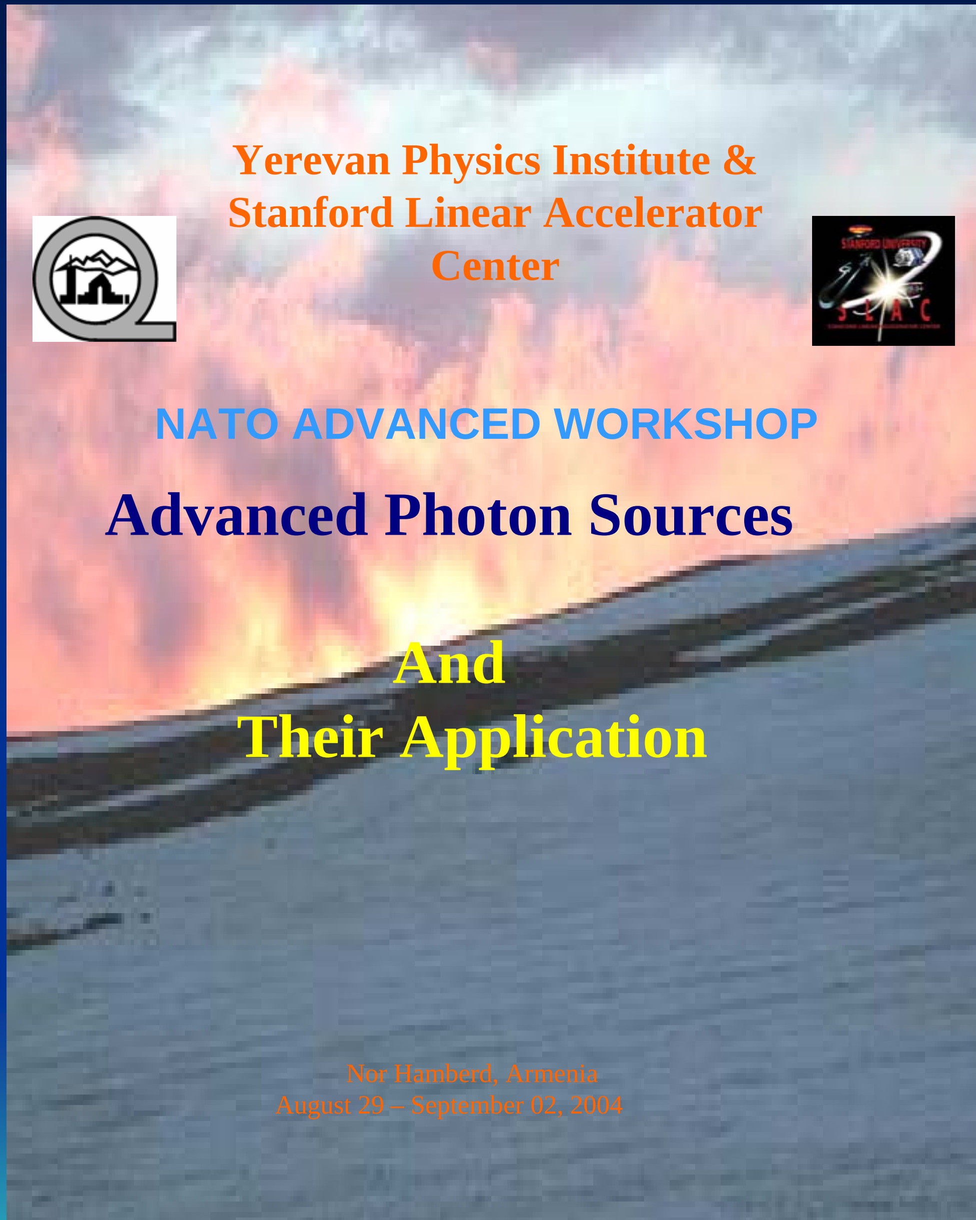
YEREVAN PHYSICS INSTITUTE



- Organized by **Yerevan Physics Institute** and **Stanford Linear Accelerator Center**
- Held at Nor Hamberd Conference Centre of YerPhI on a Mt. Aragats, 2000 m high above sea level,

Outline

1. Introduction
2. Bremsstrahlung (BS).
3. Transition Radiation (TR)
4. Parametric X-ray Radiation (PXR)
5. Channeling Radiation (ChR)
6. X-Ray Cherenkov Radiation (XChR)
7. X-ray diffracted radiation in superlattices (XDR)
8. Coherent Bremsstrahlung (CBS)
9. String Of Strings (SOS)
10. Conclusion

3rd generation photon sources worldwide:

Stanford Linear Accelerator Center — SPEAR-3

DESY — PETRA/HASYLAB

elettra — Synchrotron Light Laboratory (Trieste)

SPring-8 — Advanced Photon Source

ESRF — European Synchrotron Radiation Facility

CANDLE — Center for the Advancement of Natural Discoveries using Light Emission

Progress in variety of theoretical and experimental schemes to produce radiation from electron beams has been made at many laboratories around the world.

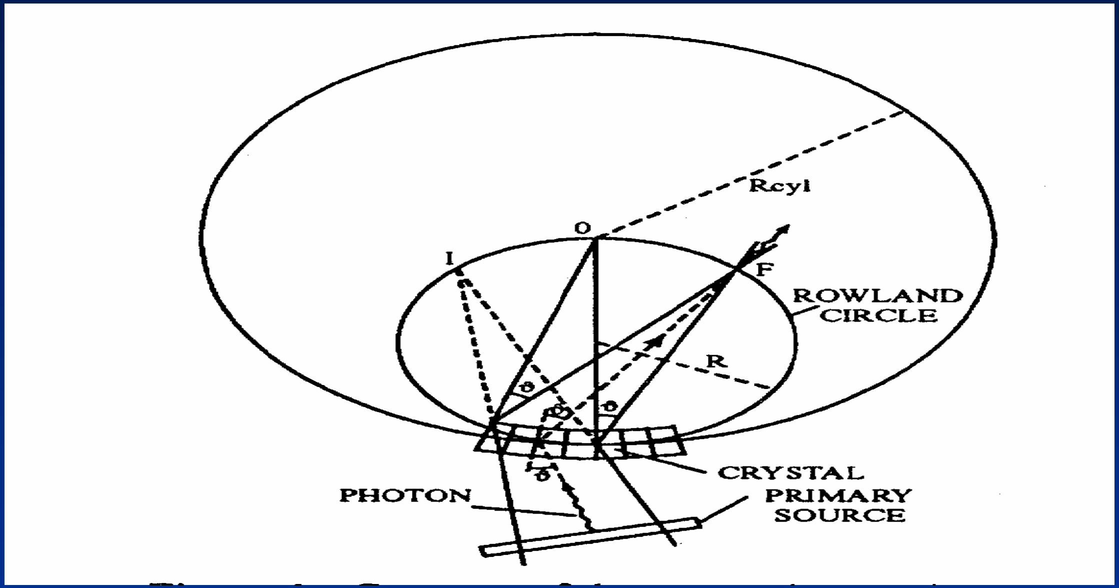
Applications: K-edge angiography

Requirements for K-edge angiography:

Duration of radiation	50-100ms
Photon energies	33.17keV
Bandwidth	1%
Flux density	$3 \cdot 10^{11}$ ph/(s·mm^2)

YerPhI

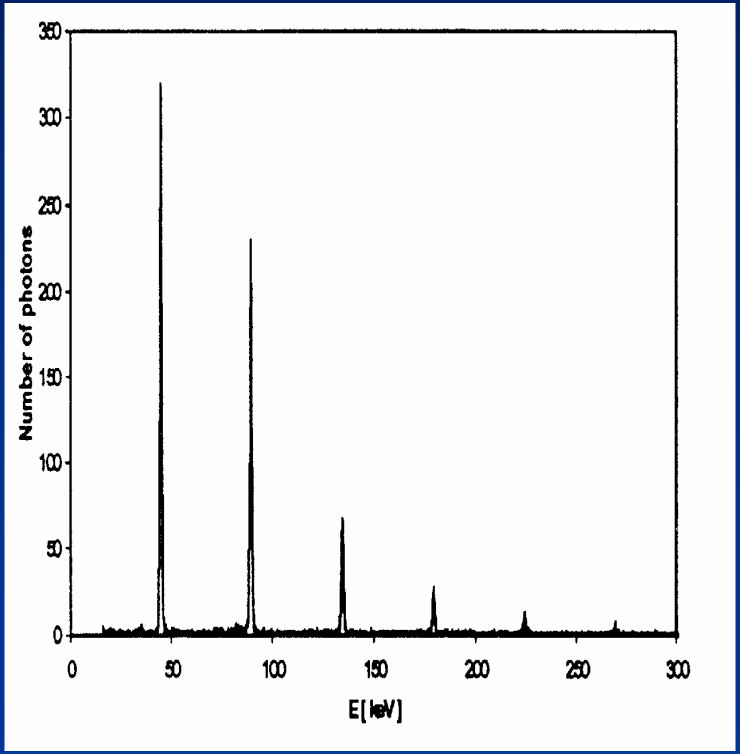
Applications: Monochromatic photons using Bremsstrahlung



Energy	**1.75-15MeV**
Intensity	**2mA**
Duty factor	**2%**
Target	**4mm (Ta/C)**
Monochromator	**4mm(Si/Ge/Cu)**

Properties of accelerator and beam

$C_{e\rightarrow\gamma} \approx 8\cdot 10^{-12}$

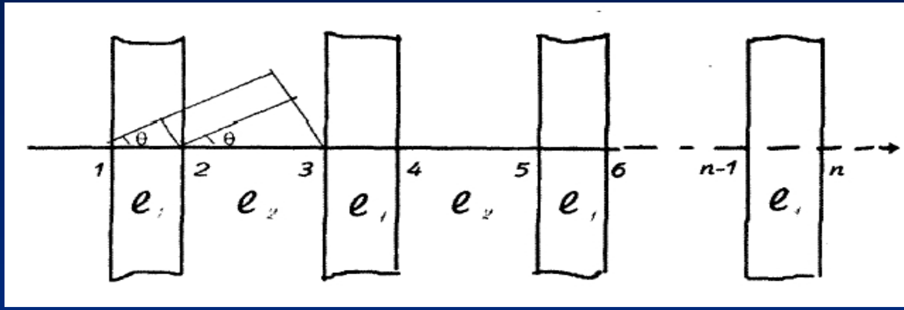


W.Mondelaers et.al., Ghent University

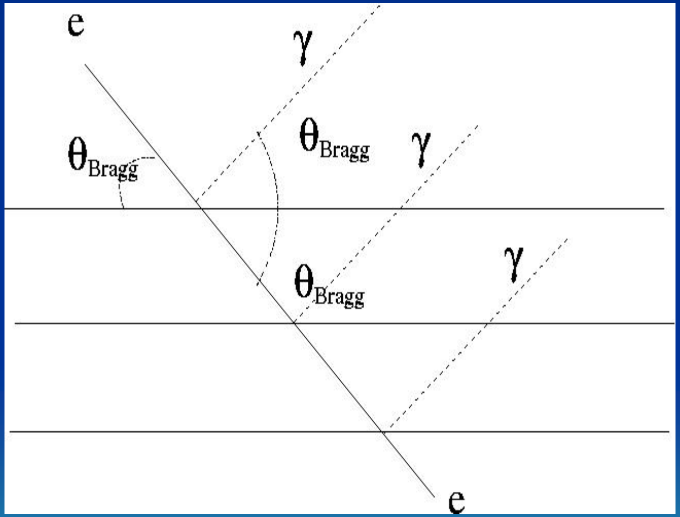
J.Jolie et.al.University of Friburg (2003)

New intensive photon sources based on Transition Radiation

- Characteristic angle ~ $2/\gamma$
- Periodic structure +TR → Coherent X-ray (observed by **K. Yamada et al., Phys. Rev., A59,(1999)3673**)



- Bragg condition → Diffracted TR or pseudophoton refraction (observed from 500MeV electrons crossing **W/B4C** multi-layer with ***d*** **= 1,24 nm**, **N.Nasonov et. al., Phys. Rev. E68, (2003) 036504)**

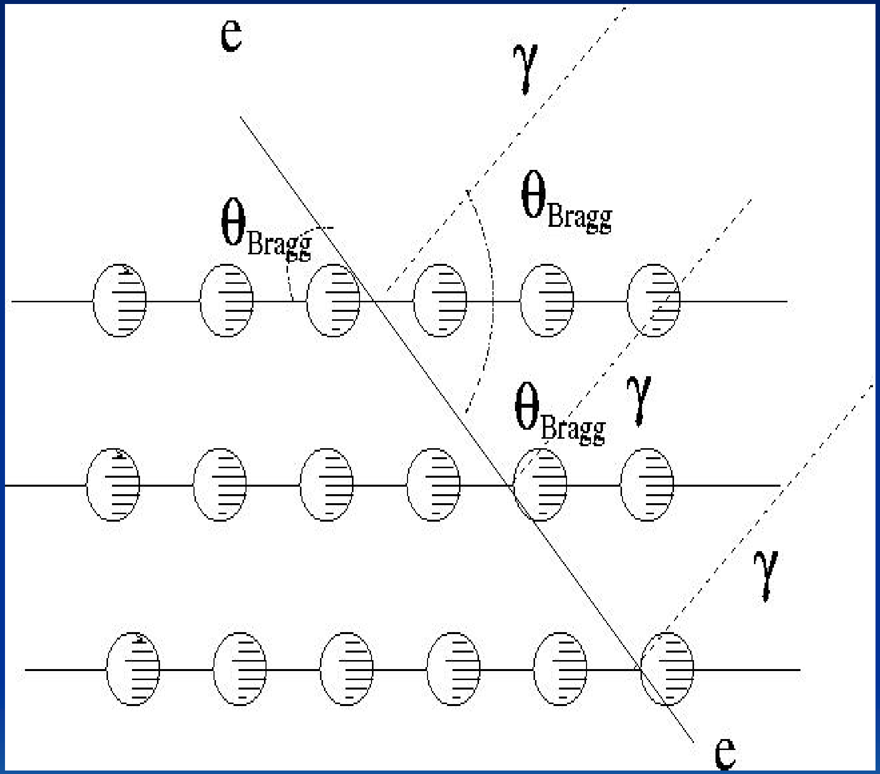


Ongoing studies of DTR by Adelphi corp. (USA)

Parametric X-ray Radiation (PXR)

Interference of pseudophotons at Bragg angles produce a spot at $2\Theta_{Bragg}$, first observed at Tomsk and YerPHI

- **Tunable energy via angle between crystal and electron beam**
- **Narrow width (<2eV)**
- **Large angles w.r.t. electron beam (low backgrounds)**
- **Narrow angular distribution and reflections allow to run several experiments**
- **Linear polarization**



PXR from multilayers

PXR dominates over DTR for

$E_e < E_{critical}(\gamma^*) = \omega_B/\omega_p$

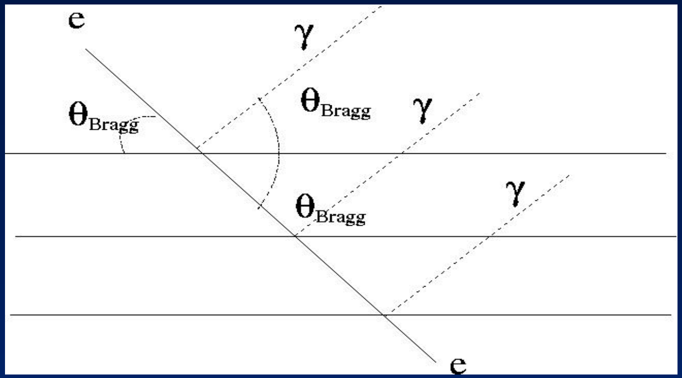
for higher energies DTR dominates

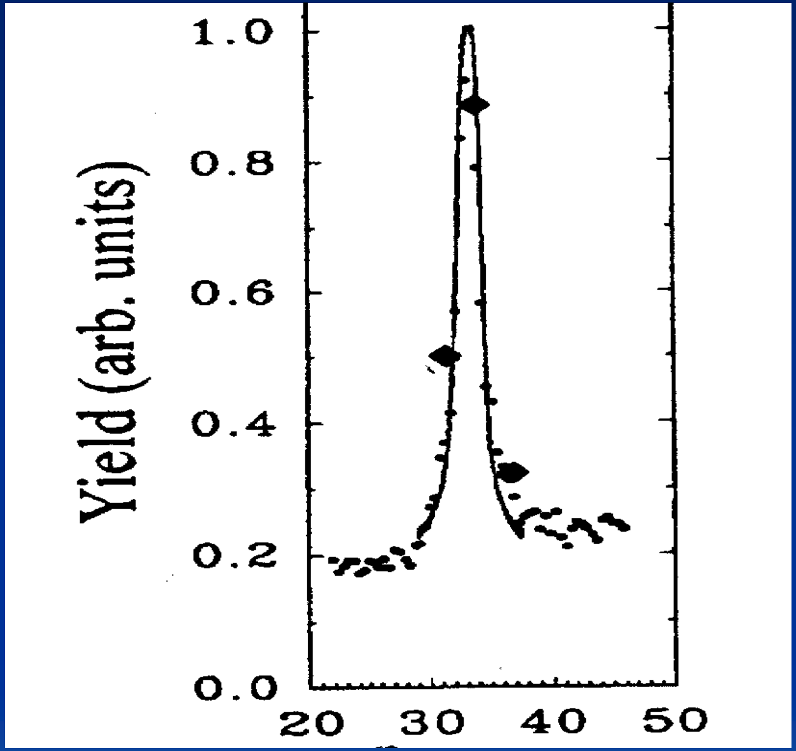
PXR for multilayer (Adelphi Corp):

10^{-4}-10^{-3} photons per electron

PXR for crystal:

10^{-6}-10^{-5} photons per electron

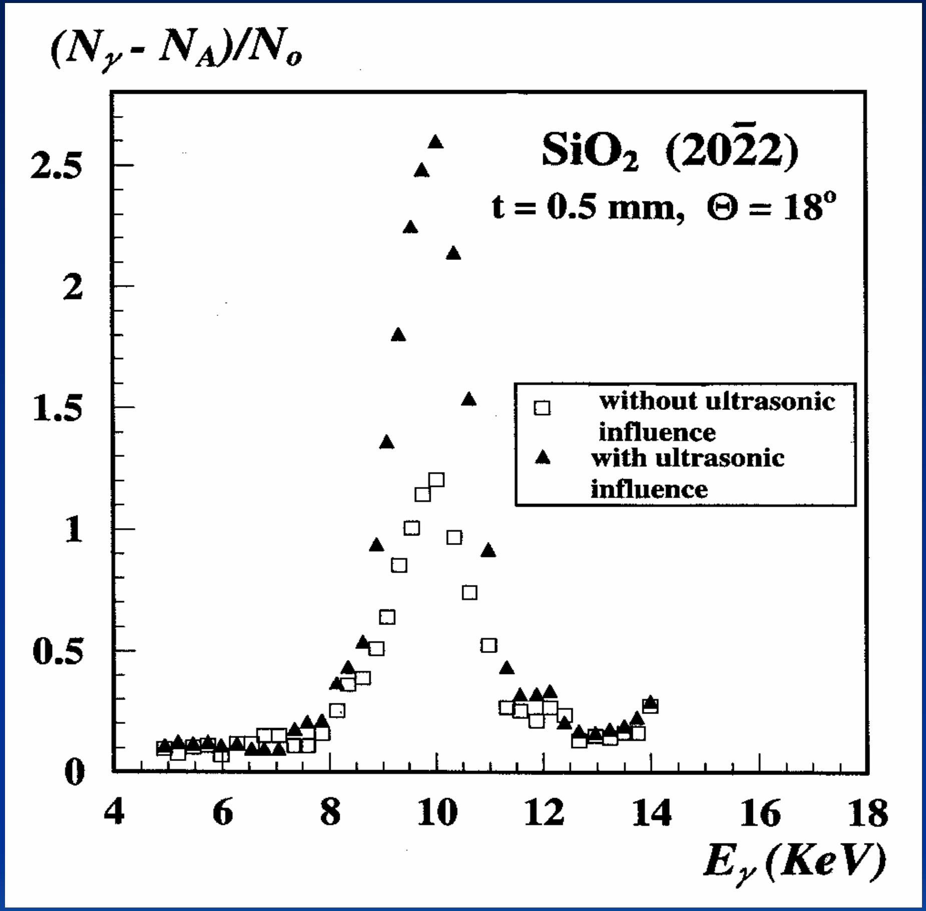




The comparison of the measured and calculated (DTR-only) orientation dependence on the collimated X-ray yield for 500MeV electrons.

Parametric X-ray Radiation in external field

Crystal distortions may lead to increase of interference effects



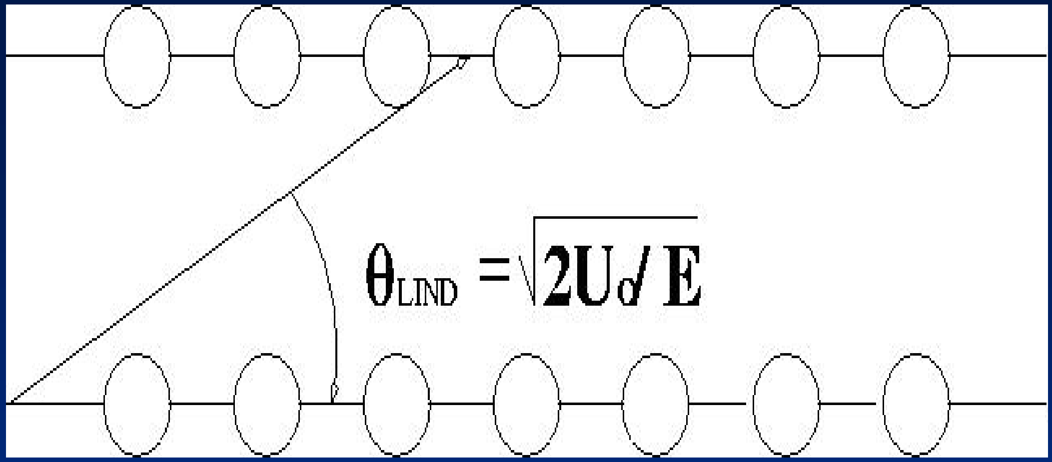
PXR spectra on SiO2 target with and without external ultrasonic influence.

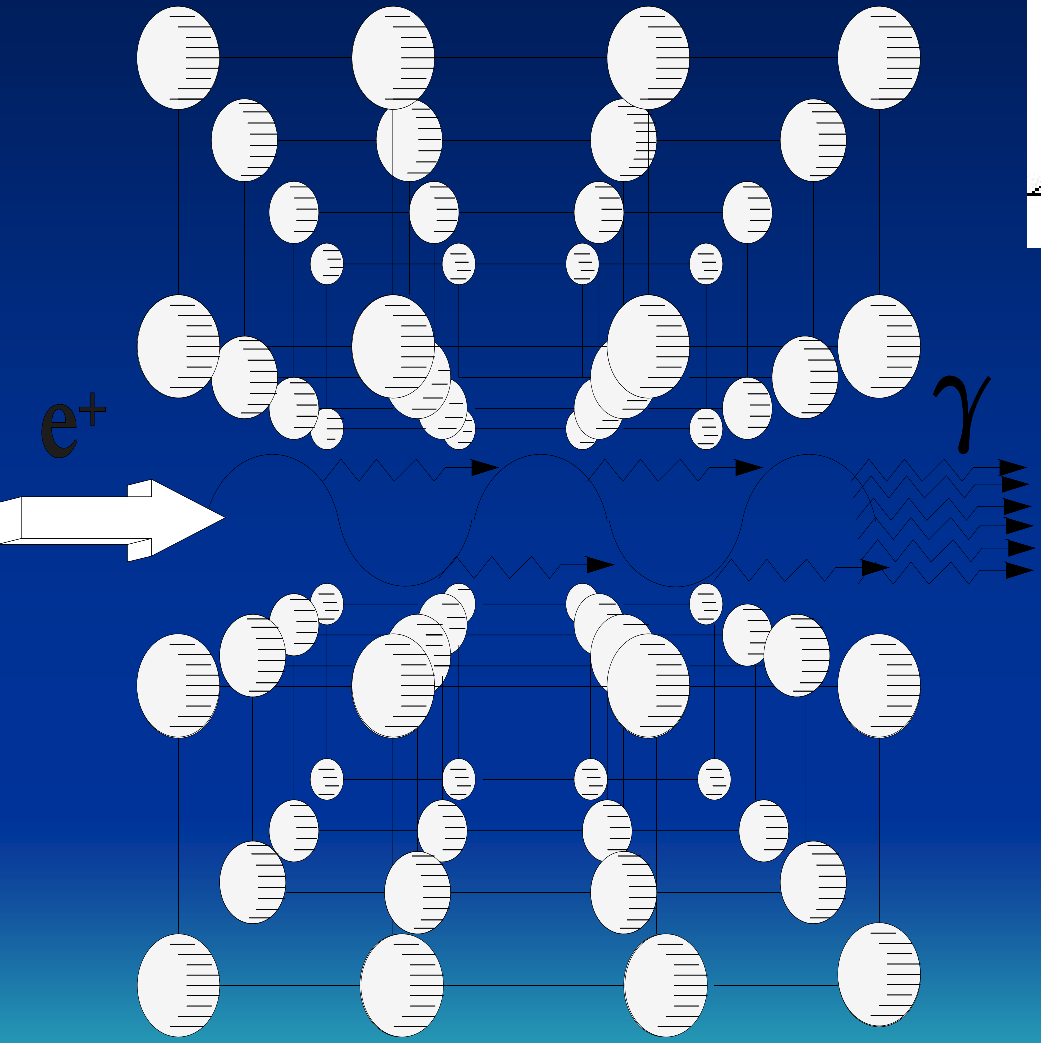
Intensity of photons increasing 2-3 times under influence of ultrasonic wave and temperature gradient!

Parametric X-ray Radiation (PXR) Applications

- Real-time imaging (pulsed X-ray source).
- Phase imaging for none destructive and medical applications.
- Explosive detection by diffraction
- Fissile material detection by edge absorption and fluorescent.
- Measurement of photon interaction cross sections.

Channeling radiation





Features:

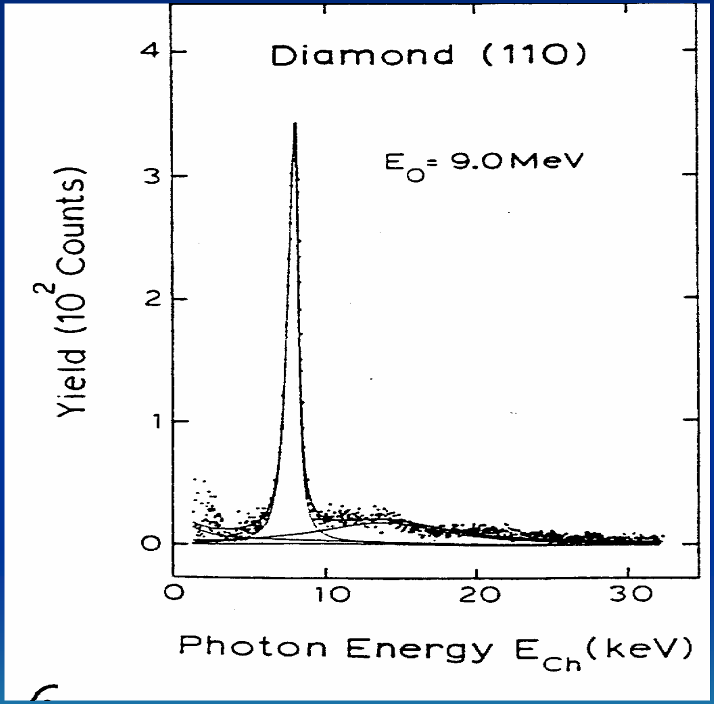
- Energetic
- Bright (10^{12} photons/s)
- Tunable (10-40keV)
- Narrow width (10%)

A PERFECT choice for applications!

Low energy Channeling Radiation Applications

First observation at Livermore by B.Berman et al.

Intensive studies at Darmstadt Superconducting accelerator with 10MeV electron beam and 0.05 mrad divergence.



Electron Energy	9 MeV
Beam current	30μA
Crystal	Diamond (plane 110, 13μm)
Photon Energy	8 keV
ΔE/E	0.1
Photon flux	10^{11} photons/s

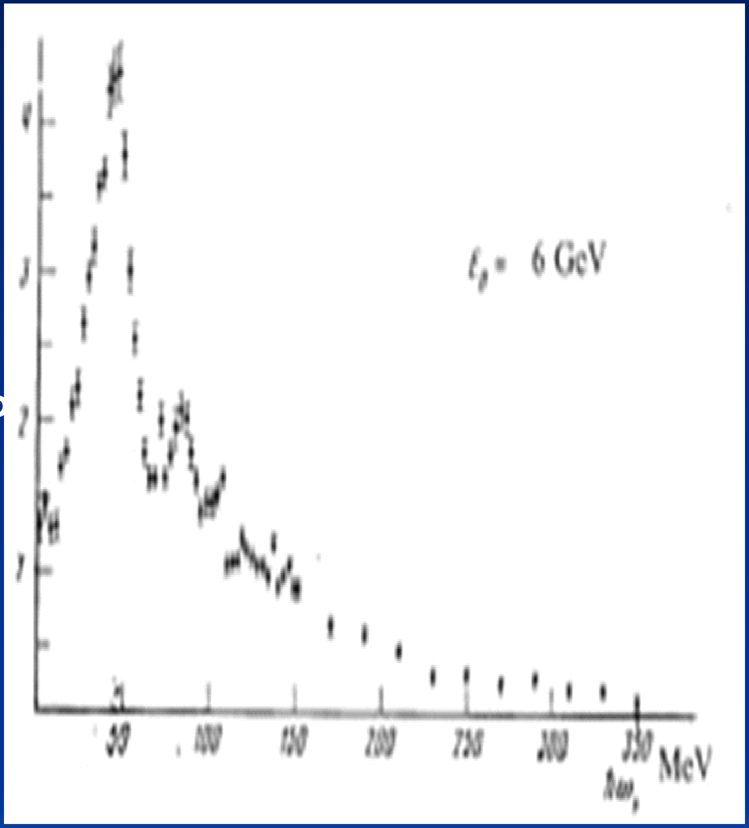
For creation X-ray sources in the energy region 10-40 keV with intensity 1011÷10**12 photon/sec by using channeling radiation on crystal new investigations are needed.**

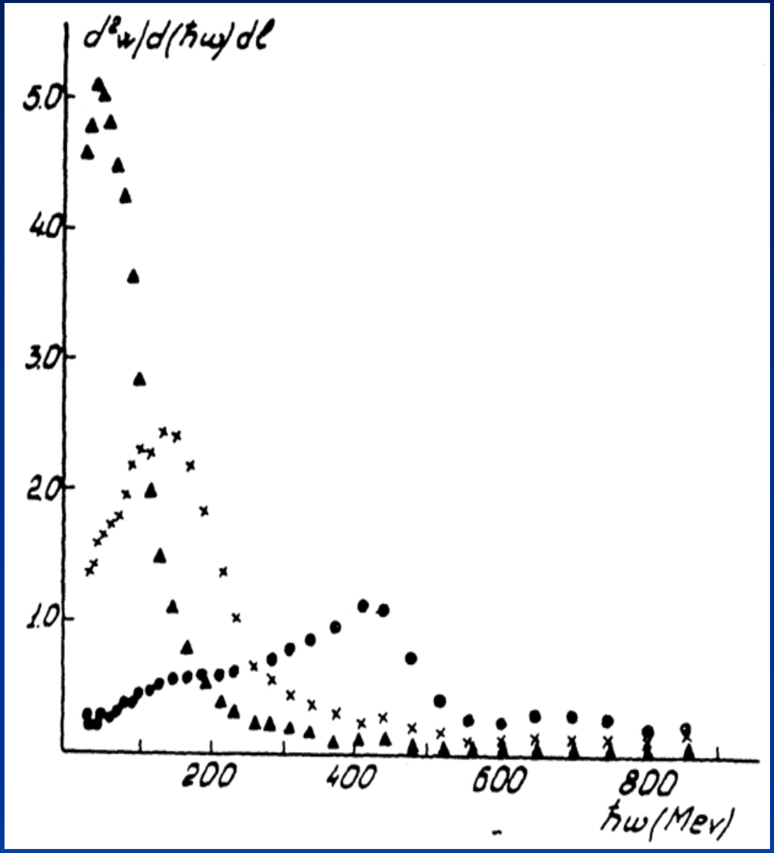
High Energy Channeling radiation

Predicted in 1976
(Kumakhov JETP)

First measured at
SLAC for e+ in 1979
(R.Avakian et al. JETP

Effect on e- observed
at Yerevan,Kharkov,
Tomsk,CERN

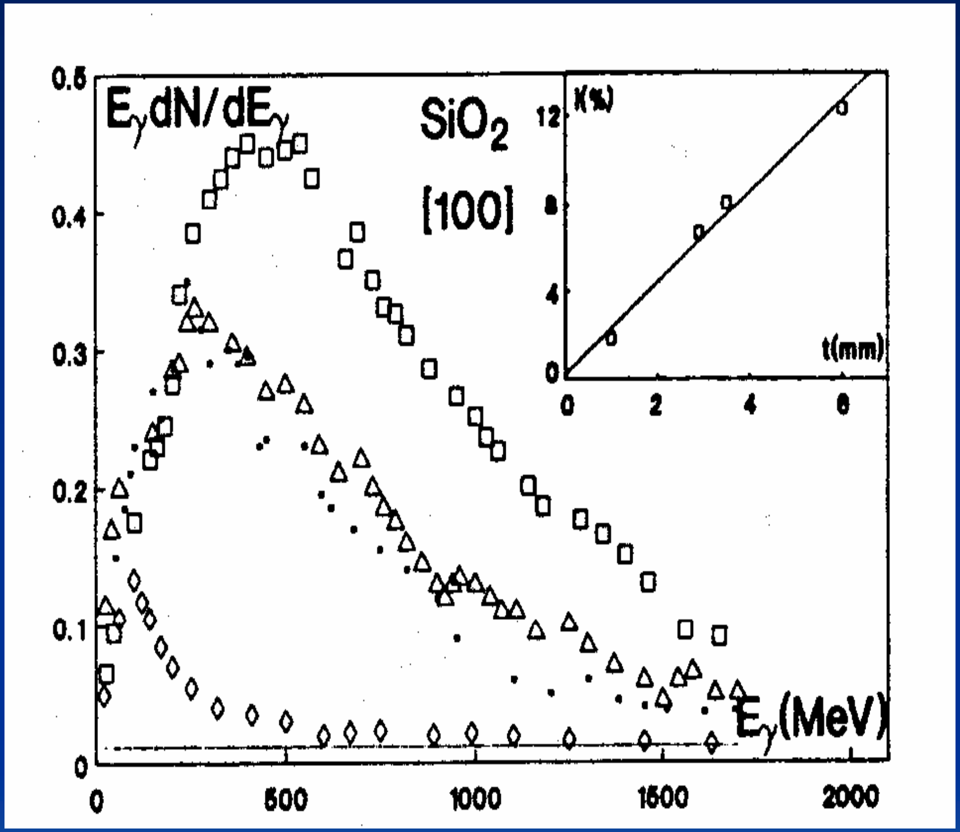




Peak structure for e+ channeling
Spectra for 6 GeV at SLAC

e- spectra for different
incident angles

Channeling radiation in piezoelectric crystals

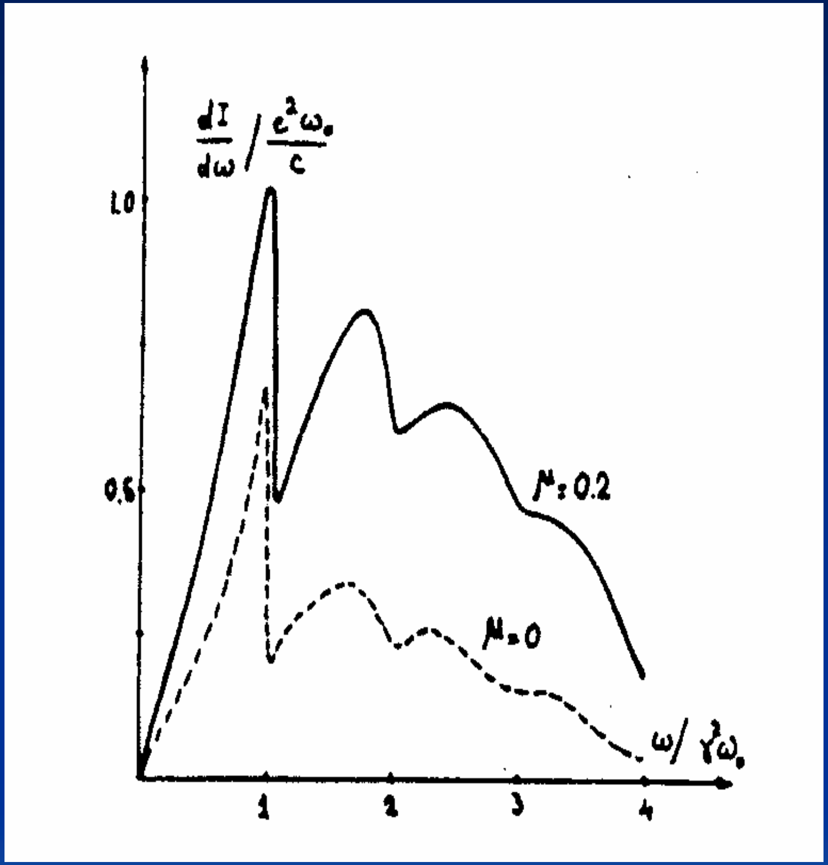


Channeling radiation spectra
for different quartz radiators

Use of piezoelectric crystal as radiator allows channeling studies in presence of ultrasonic waves

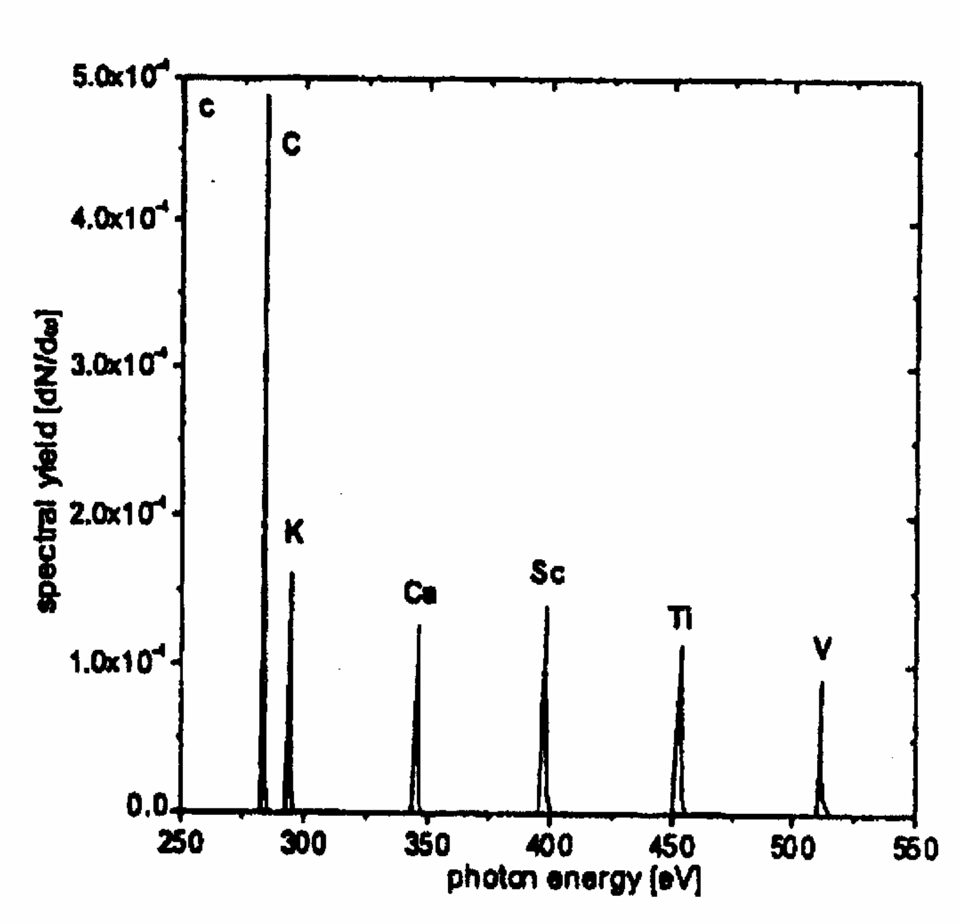
Quartz is an effective radiator for ChR, CB and pair production studies in single crystals

Channeling radiation in the external field



Significant enhancement of channeling radiation of positrons predicted in the presence of the ultrasonic wave

X-Ray Cherenkov Radiation



The soft X-ray region the Cherenkov radiation is characterized by a single-line spectrum and by forwardly directed emission and only requires low- relativistic electrons from a laboratory-sized accelerator.

W.Knulst App.Phys.Lett (2001)

X-ray diffraction radiation in superlattices (XDR)

Recently the new kinds of superlattices were discovered in fullerenes. It was demonstrated that fullerites and nanotube ropes may serve as good enough Bragg mirrors for soft X-ray radiation with wavelength up to 20Å and higher.

Crystalline Undulator Radiation

In a periodically deformed crystal channeled particle will do oscillation motion in addition to the higher frequency usual channeled oscillation, leading to production of CUR.

This process was first considered by V.Kaplin et al (1980). The theory of CUR has been developed (Soloviev, Grenier, R.Avakian et al 2003)

There were many proposals to prepare crystalline undulator but only S.Bellucci et al (2003 90/034801) has succeeded to make one.

Biryukov et al have started some experiments at Serpukhov and Frascati to observe CUR.

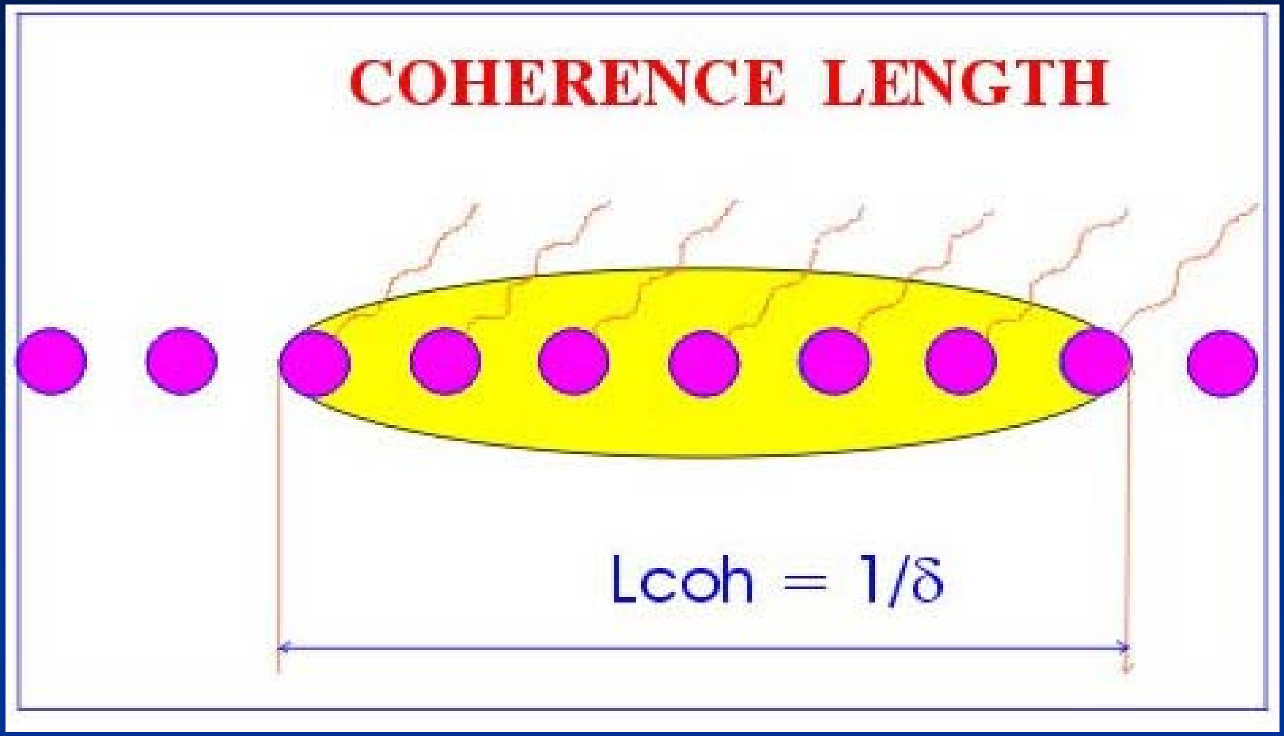
summary

Type of radiation	E(MeV)	Radiator	L(cm)	W (keV)	$\Delta w/w$ (%)	N'(ph/e/cm^2)	
Brems strahlung	15	C+ Rowland	0.4 C+Si	20-100	< 2	>8.10^{-12}	
Transition radiation	15	10 pairs of ~200 nm (Ni/C)	0.0004	2-6	20-60	2.10^{-6}	
X-ray Cherenkov radiation	10	V, Ti	0.001	0.45, 0.52	< 0.1	$5 \cdot 10^{-6}$	
Parametric X-ray radiation	70	LiF(200), C(002) (HOPG)	$L > L_{abs}$	12.5	< 0.1	~$4 \cdot 10^{-5}$ 10^{-6}	
Channeling radiation	10	Diamond (110)	0.02	2-15	~20	$4 \cdot 10^{-6}$	

Requirments for medical and material science applications

- high current, low energy (10-25MeV), low emittance superconducting CW accelerators for many applications;
- radiators which could withstand high electron currents (few hundred μA – 2mA);
- new generation of detectors for detecting high-current photon fluxes;

COHERENT BREMSSTRAHLUNG



M.L. Ter-Mikaelian
1923-2004

M. Ter-Mikaelian, 'High-Energy Electromagnetic Processes in Condensed Media', Wiley-Interscience, New York, London, Sydney,Toronto, 1972.

The coherent length in BS is inverse proportional to the longitudinal momentum transfer, could be very large at high energies. In oriented crystals because of the large coherent length many atoms can irradiate coherently.

COHERENT BREMSSTRAHLUNG

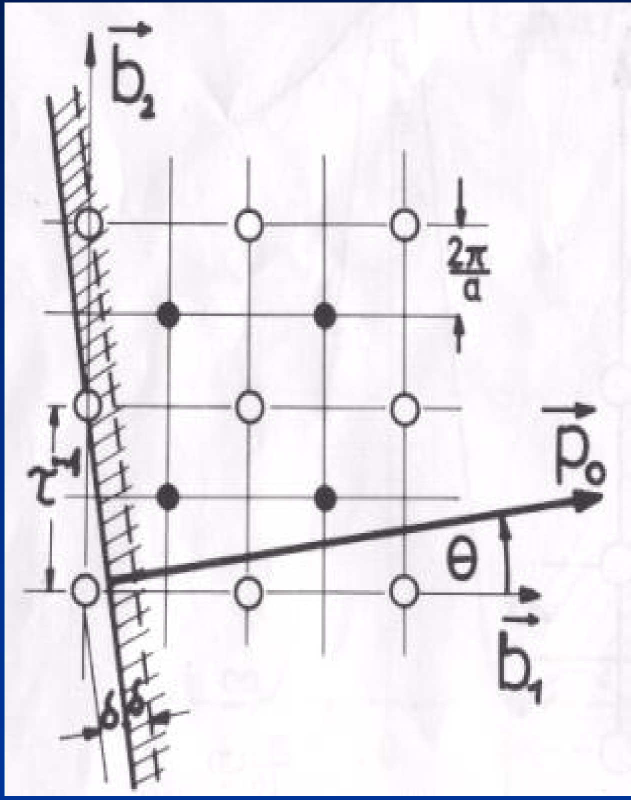
CB connected to the periodic structure of the crystal.

The position of the hard photon peak in **P**oint **E**ffeact (**PE**) orientation is given by

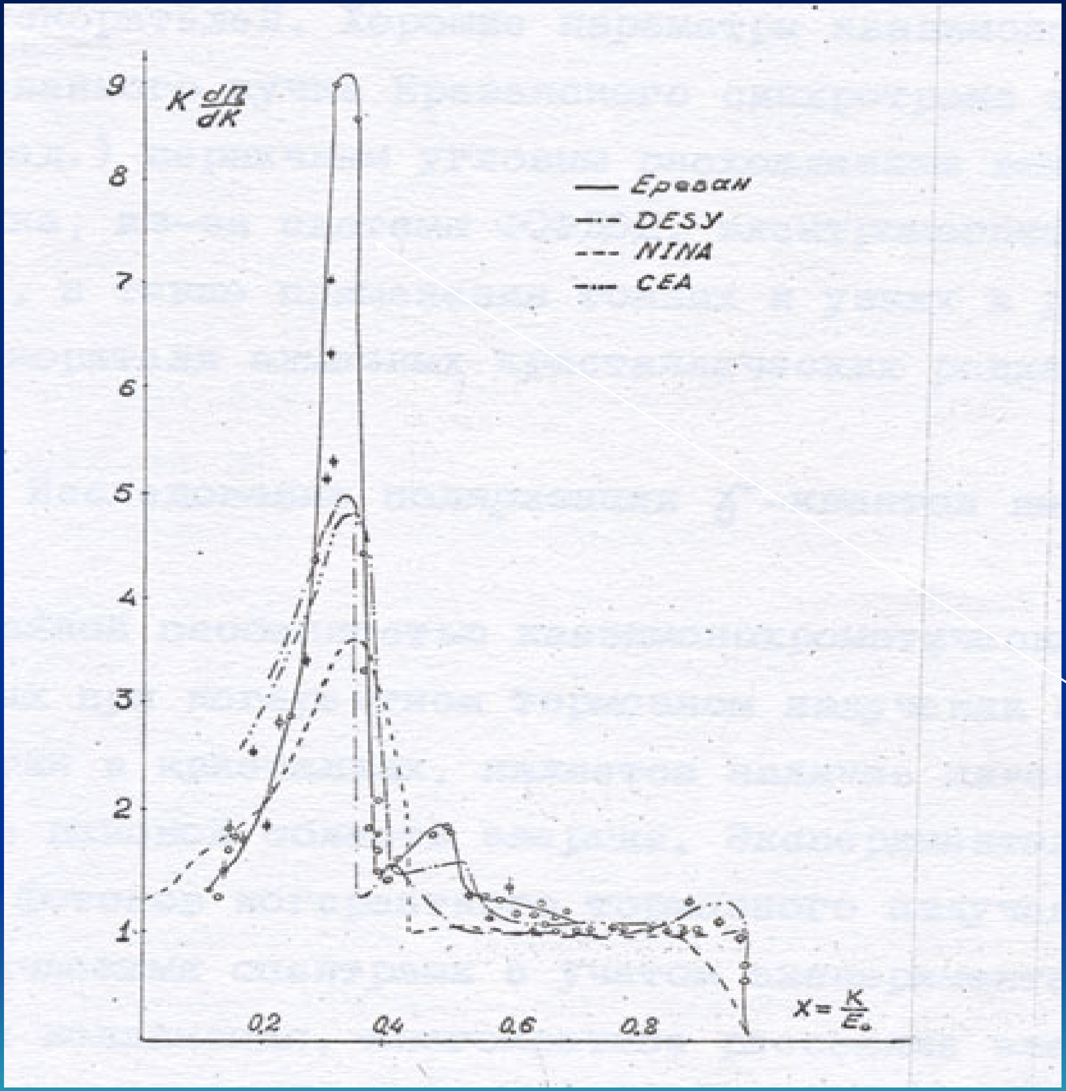
$$\theta = (a/4\pi\lambda_C\gamma)(E_\gamma/(E_o - E_\gamma))$$

a is the interplanar distance and θ the electron incident angle with respect to the plane.

For the **String Of Strings** orientation **a** is the spacing between the axes (strings) forming the planes, and θ, the electron incident angle with respect to the axis.



COHERENT BREMSSTRAHLUNG

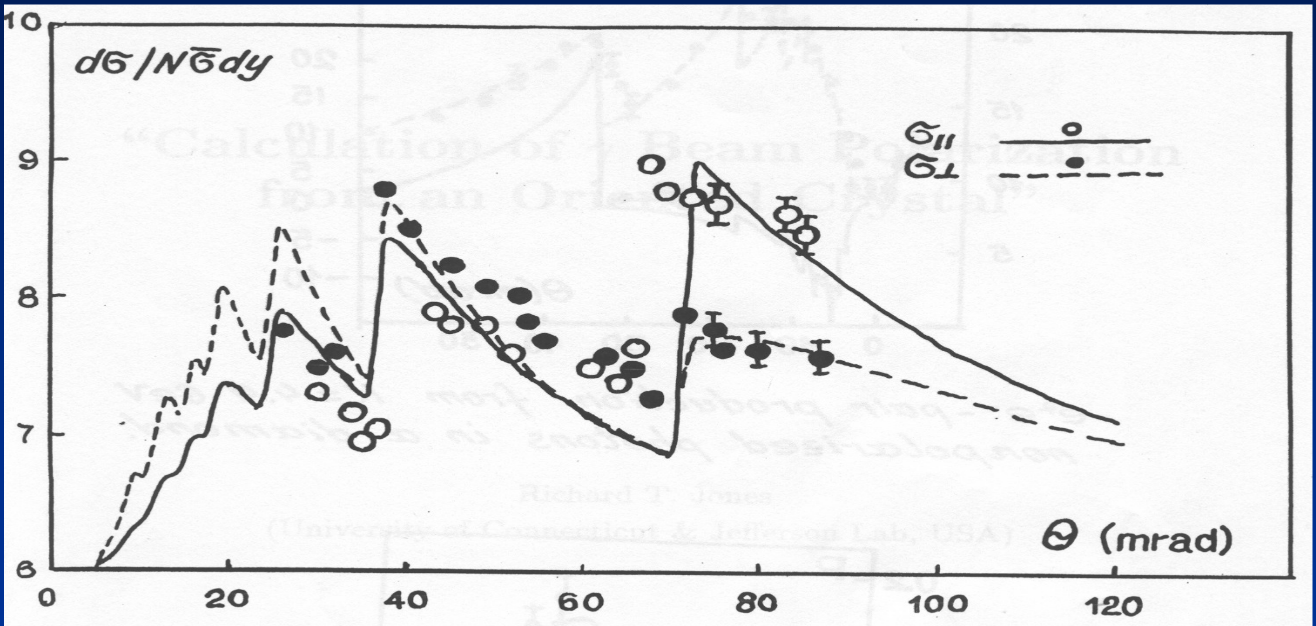


Coherent to incoherent ratio gives info about the photon polarization

Highest polarization measured at YerPHI, 1975 (P=90%)

Measurement of polarization

YerPhi-1975



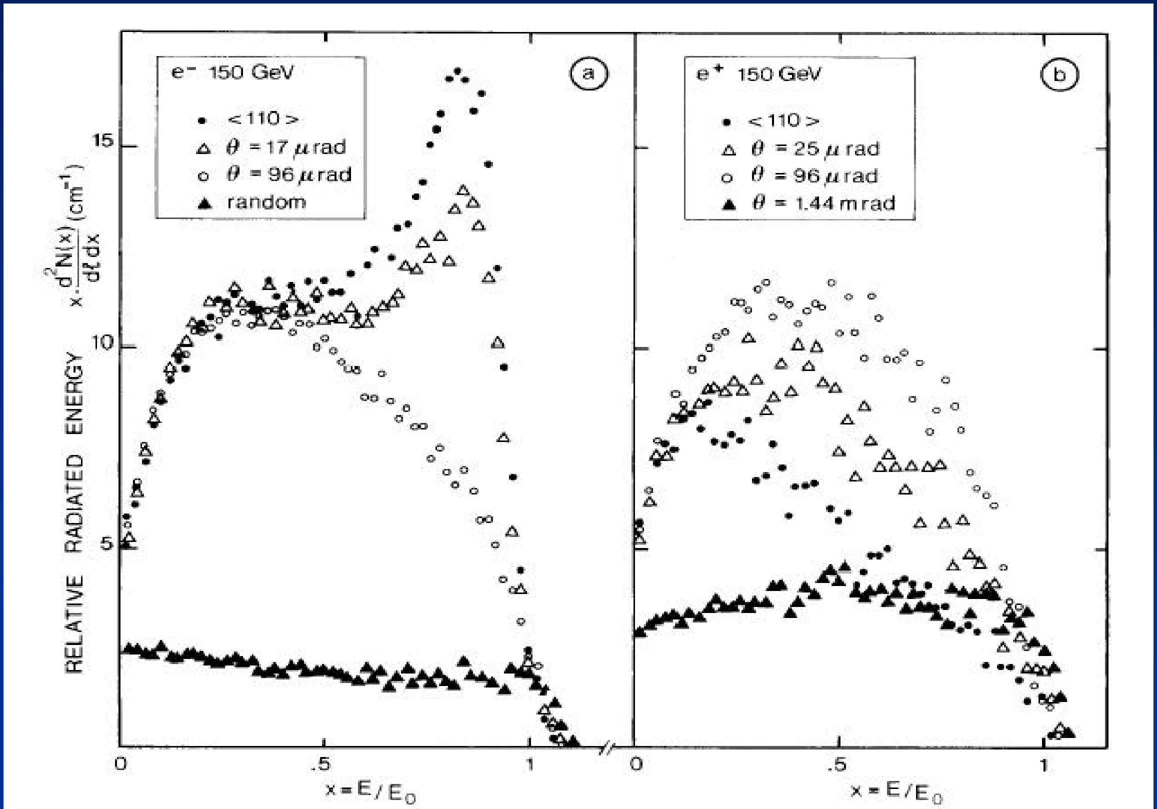
Photon polarization leads to observable asymmetry of pair production x-sections for in-plane and transverse to plane polarizations.

Angular dependence of coherent pair production used to measure the photon polarization

Polarization of high energy photons could be measured also by pair production in amorphous target by using appropriate range of azimuthal and polar angles of pairs (Dallakyan 2004)

SOS Radiation

SOS combines high intensity of Channeling and high energies of photons from CB



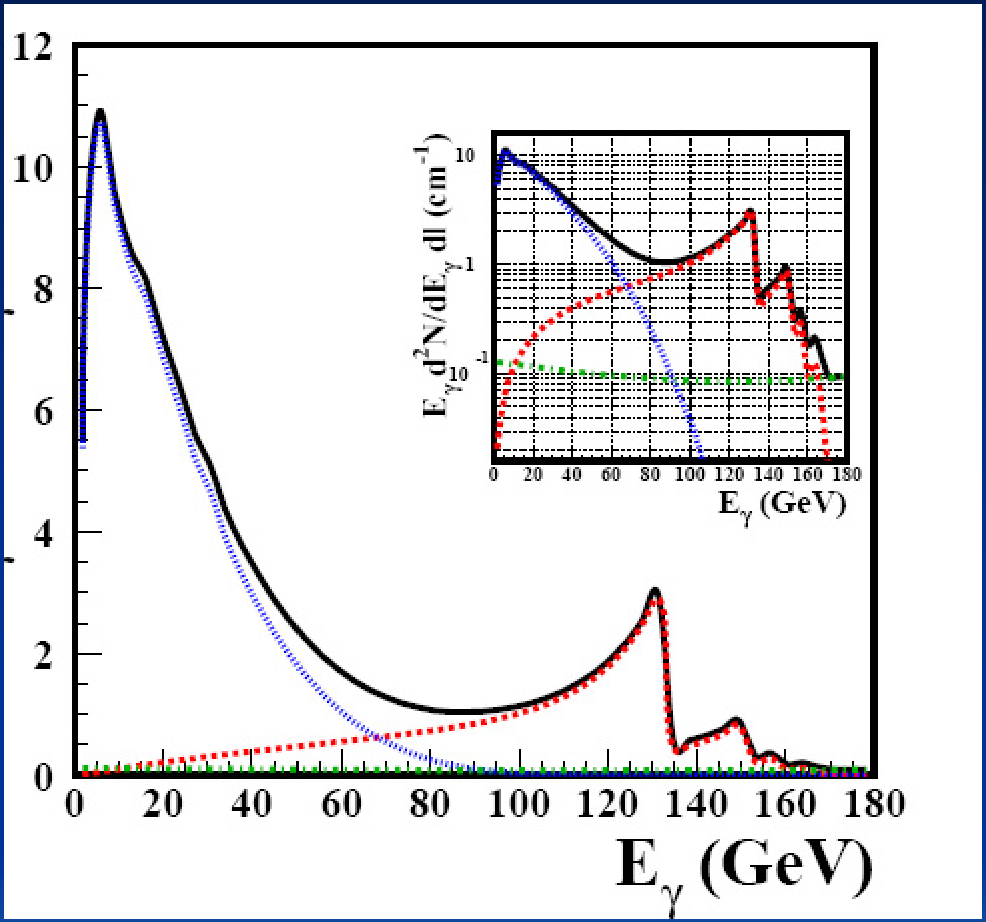
A.Belkacem, et al.New Channeling Effects In the Emission of 150GeV Electrons in a Thin Germanium Crystal
Physics Letters B, v177,2 1986

- Peak structure observed for e- in SOS regime.
- Significant difference observed for e+/e-

Observed structure triggered further studies at CERN

SOS Radiation

Ed2N/dEdl



NA-59, CERN (2002)

178GeV electron beam incident within the silicon(110) plane and at an angle of = 0.3mrad to the < 100 > axis.

Planar Chaneling radiation (linearly polarized) dominates at low energies (can be used for calibration).

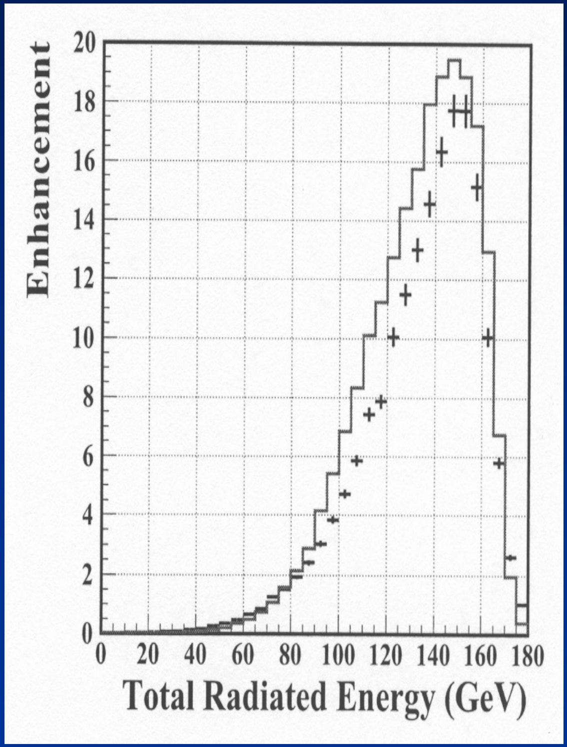
SOS radiation peaks at high energies.

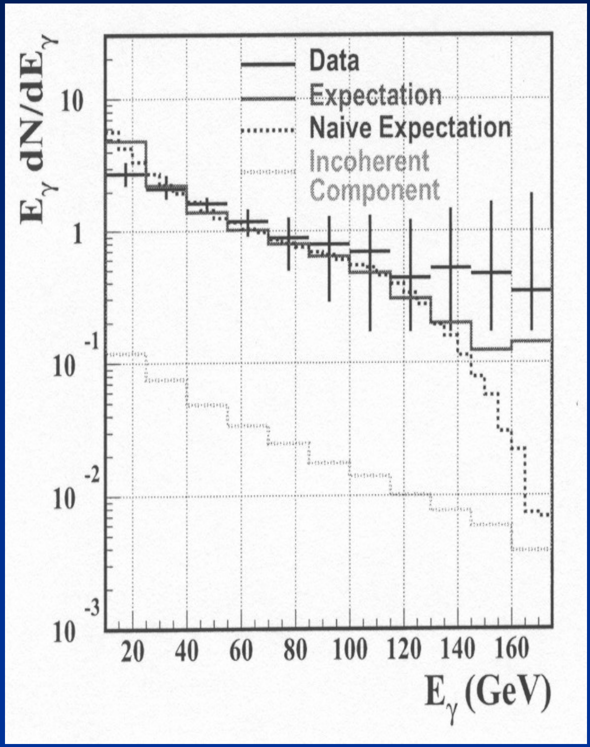
Enhancement of a factor of about 30 for SOS radiation at 129GeV.

Green - ICB, blue - PC, and red - SOS radiation.

SOS Radiation

NA-59, CERN

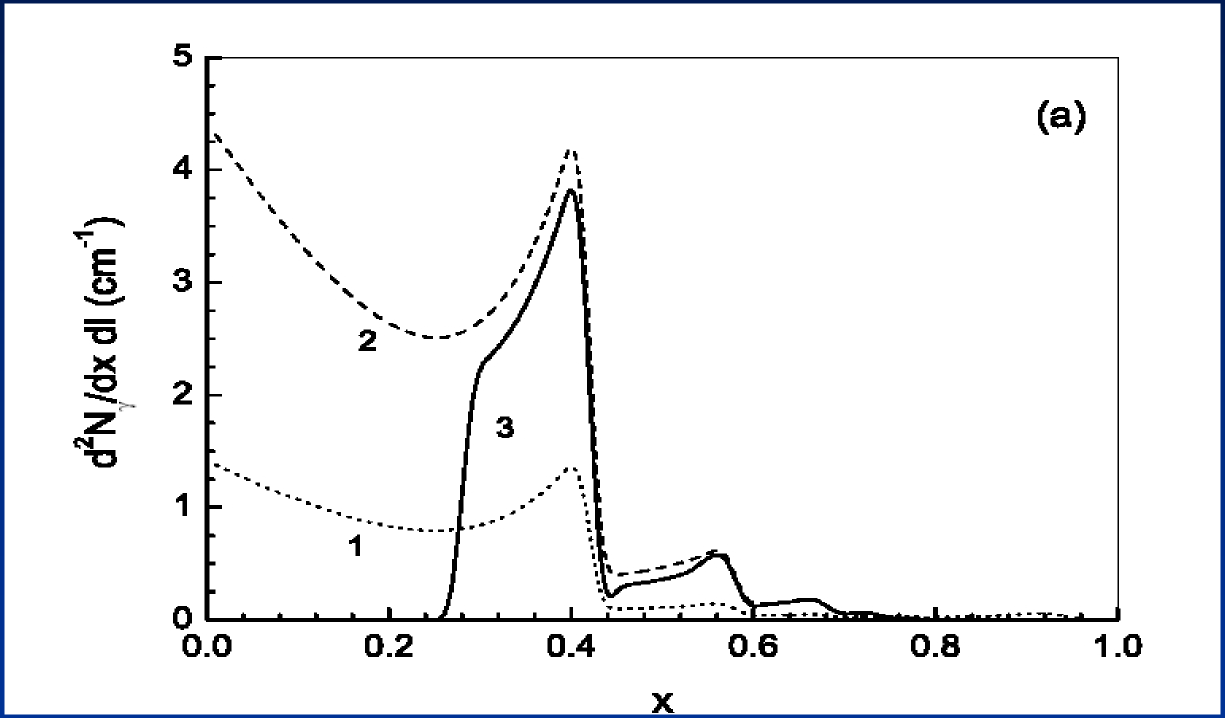




Total energy los of 178 GeV e- in SOS regime

Spectra of radiated photons measured by PS in 1.5cm silicon crystal

SOS Radiation: Theoretical interpretation

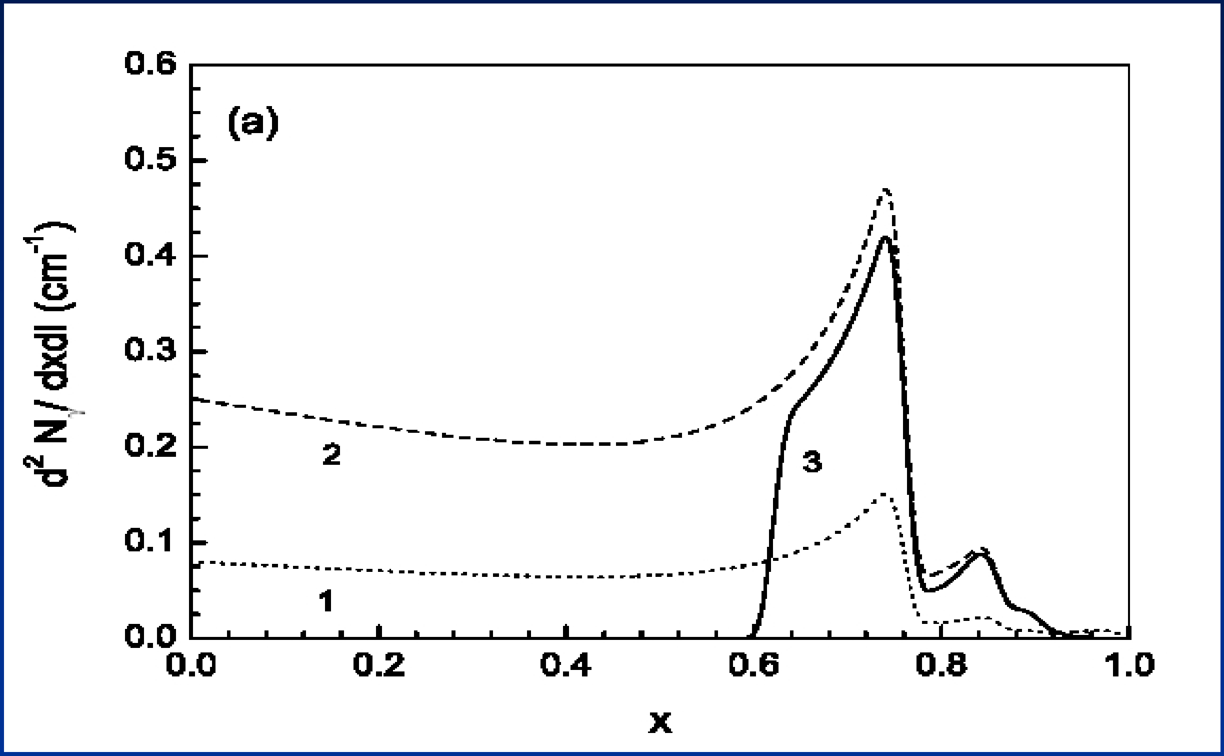


E = 12 GeV and
ω_{max} = 5 GeV

Near (001) plane and < 110 > axis, for noncollimated spectra at SOS (2), collimated within $\theta col = 4 \cdot 10^{-5}$ (3), PE (1) (V.Strakhovenko)

Enhancement at SOS orientation with respect to PE ~3-4 times

SOS Radiation



E = 12 GeV, ω_{max} = 9 GeV

Enhancement at SOS orientation with respect to PE ~3-4 times in all accessible kinematic range

(001) plane and < 110 > axis, noncollimated spectra (2), collimated within $\theta col = 4 \cdot 10^{-5}$ SOS spectrum (3) , PE (1) (V.Strakhovenko 2004)

SOS radiation has high circular polarization

Summary & Outlook

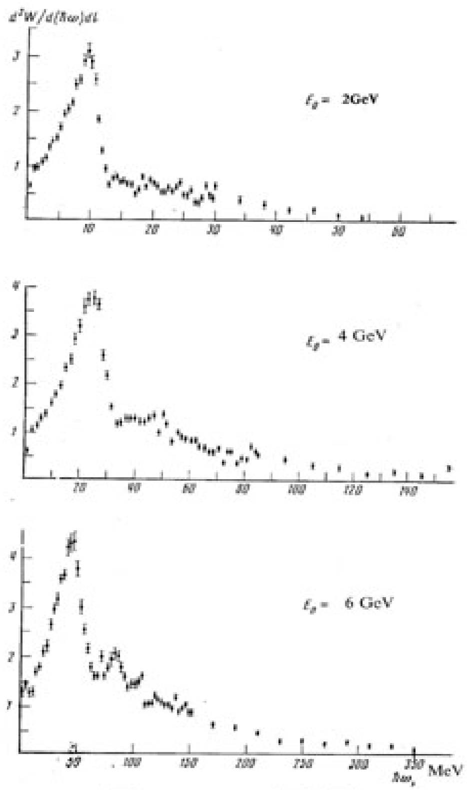
Variety of different types of charge particle radiations are under study, to develop photon sources in a wide energy range for different applications including medical and new generation of detectors

SOS orientation of single crystals significantly increases the intensity of high energy photon radiation with respect to standard CB

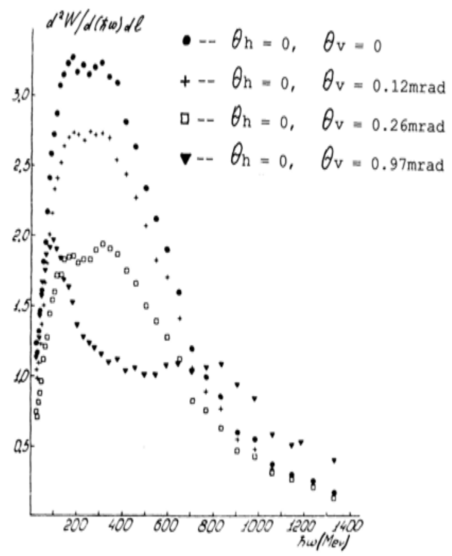
More detailed studies of channeling and SOS radiations (angular distributions, collimation,….) needed for development of a new source for high energy photons.

Support plots……..

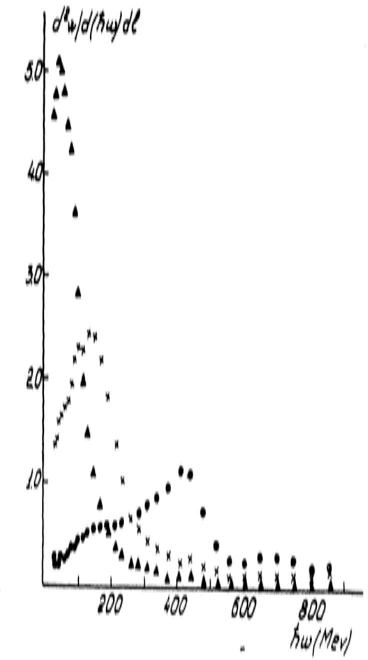
High Energy Channeling radiation



Spectral distribution of positron radiation for E=2, 4, 6 GeV

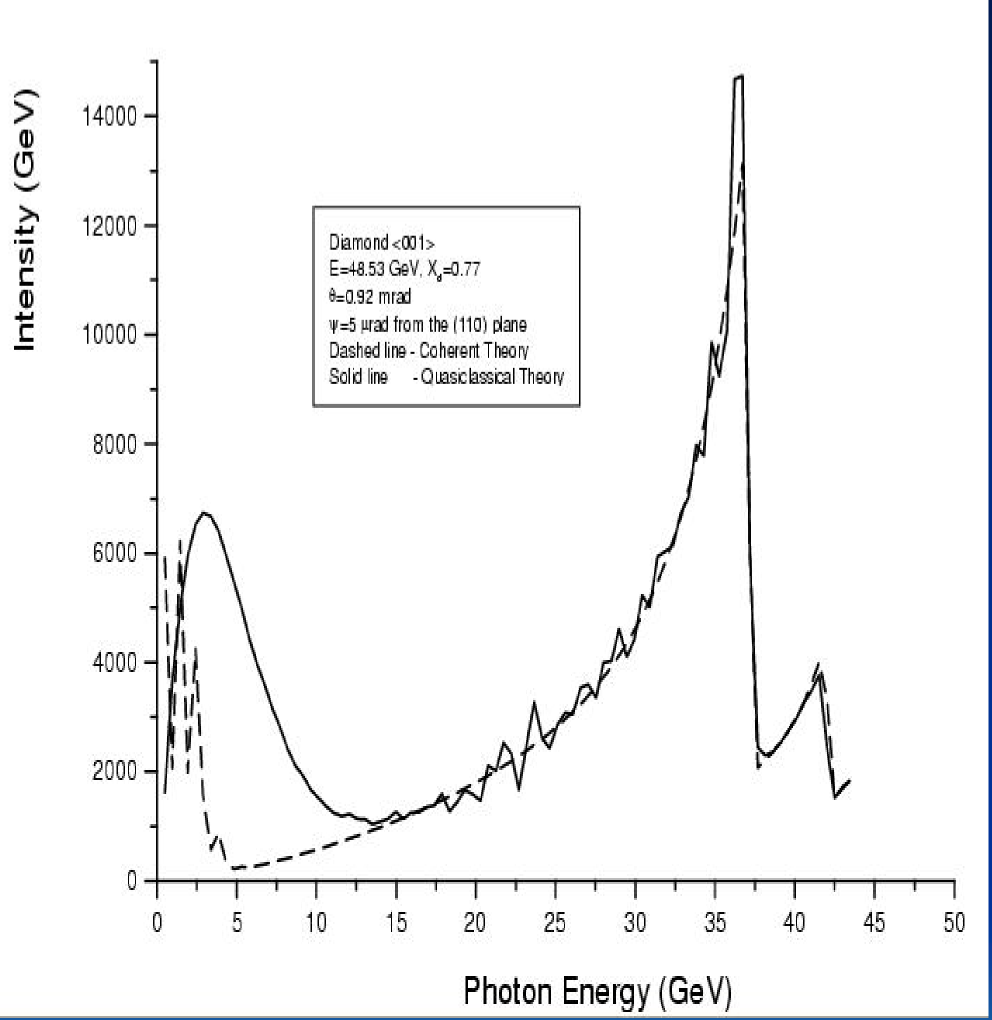


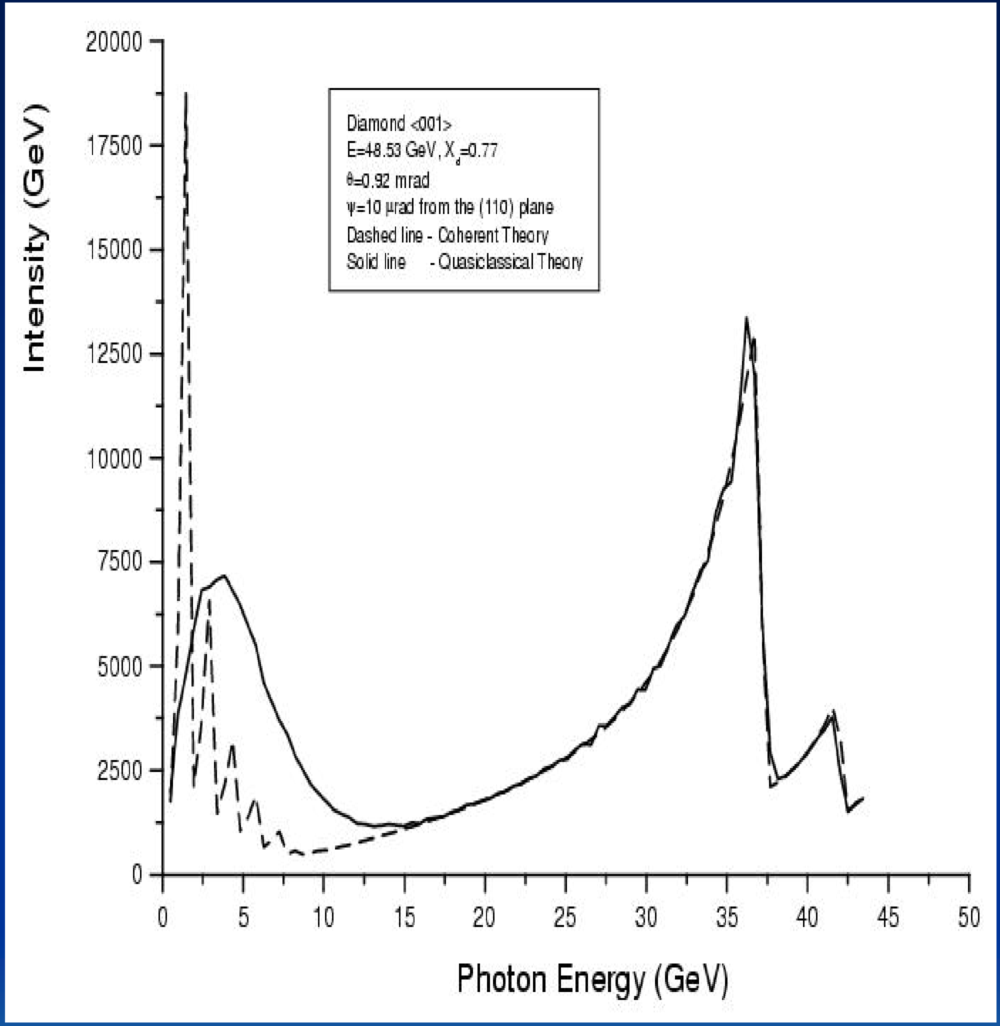
Spectral distribution of electron radiation by axial channeling in diamond crystal 1.0mm thickness



Spectral distribution of electron radiation in planar channeling in 0.1 mm thick diamond crystal. ▲ Θ_H=55 mrad, Θ_V=0; × Θ_H=55 mrad, Θ_V=0.22 mrad; ● Θ_H=55 mrad, Θ_V=0.65 mrad. Θ_H and Θ_V are the rotation angles in the horizontal and vertical planes of the goniometer, respectively.

SOS & CB





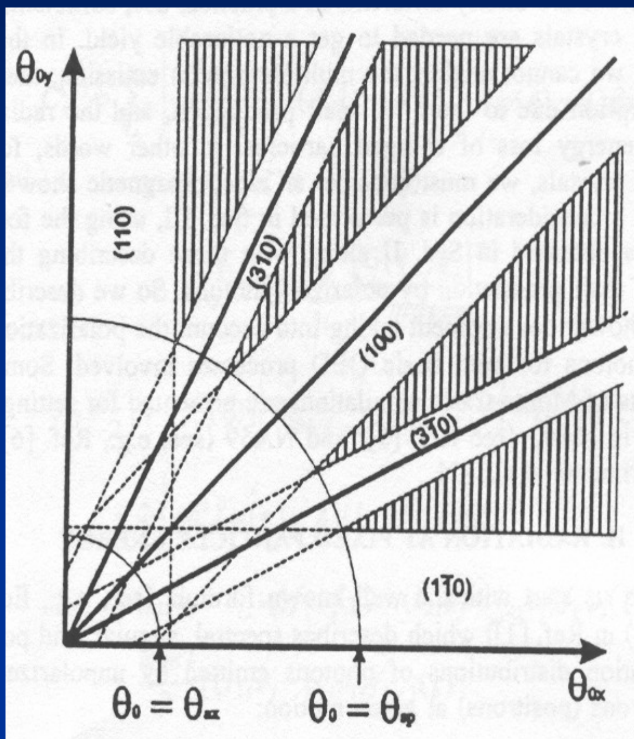
At high energies ???????

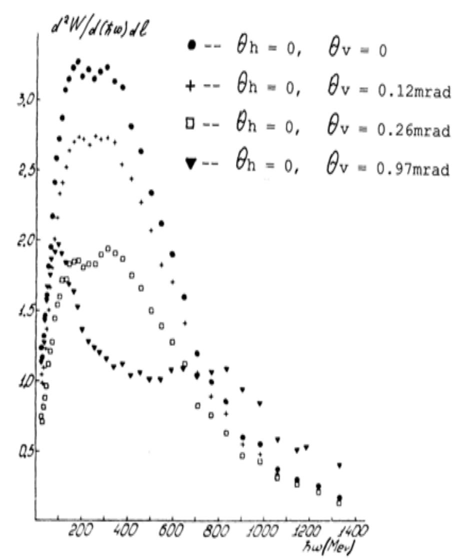
Parametric X-ray Radiation (PXR)

Problems:

- **To find the most suitable crystal material (graphite, Silicone, Germanium, Metallic Crystals).**
- **To optimise the crystal thickness for a given X-ray energy.**
- **To investigate the effect of the electron beam divergence.**
- **To calculate the effect of electron straggling in the Crystal using Monte Carlo Method**
- **To investigate PXR production in the Laue and Bragg geometries.**
- **To design a crystal target for high electron beam currents while addressing heat and charge transfer problems.**

High Energy Channeling radiation





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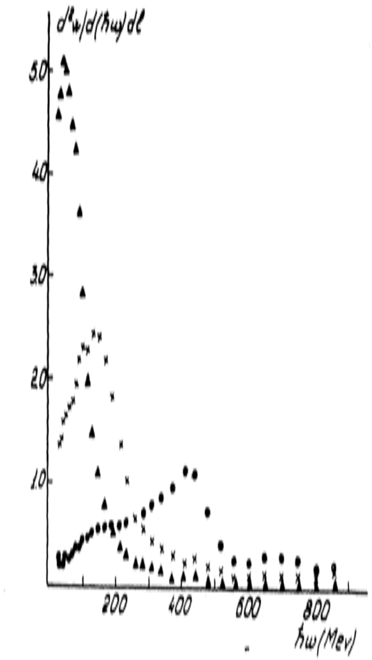

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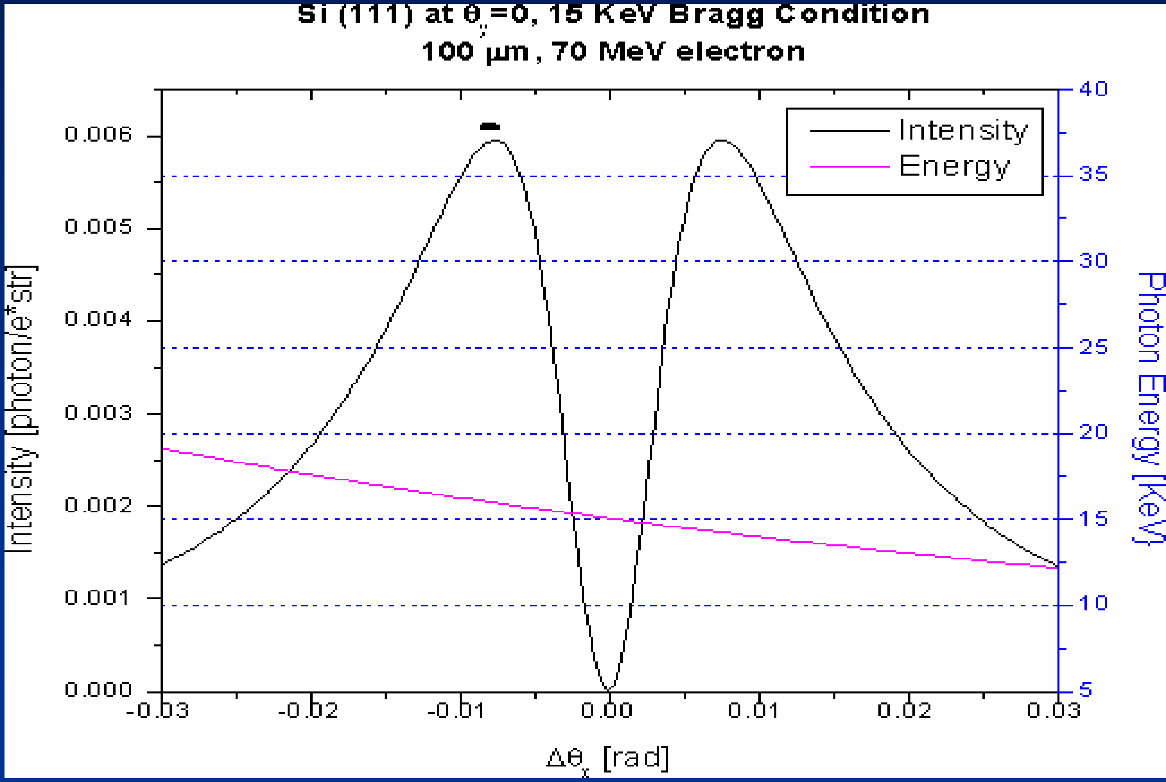
Parametric X-ray Radiation (PXR)

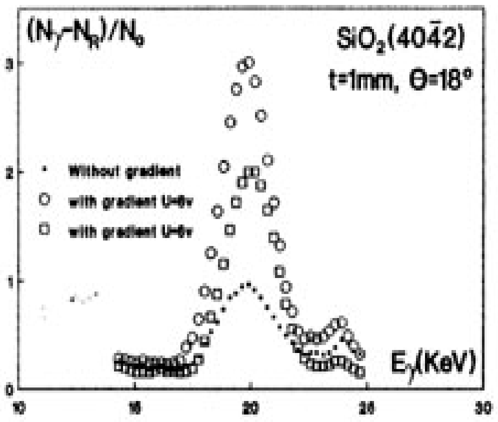


Angular and energy distributions of PXR. The with of the small line above the left peak represents the detector solid angle resolution

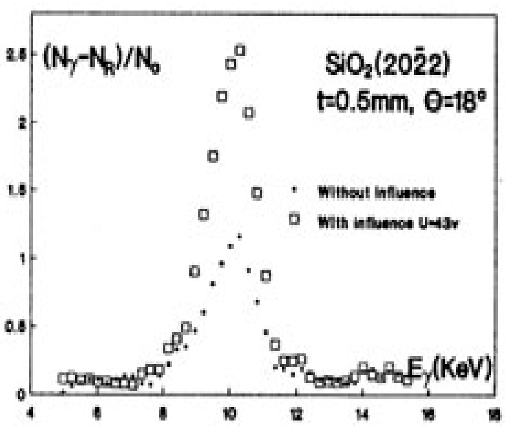
M.A. Piestrup et al, **Rev. Sci. Instr. 72, 2159, 2001**

Parametric X-ray Radiation

QUASI-CHERENKOV EMISSION



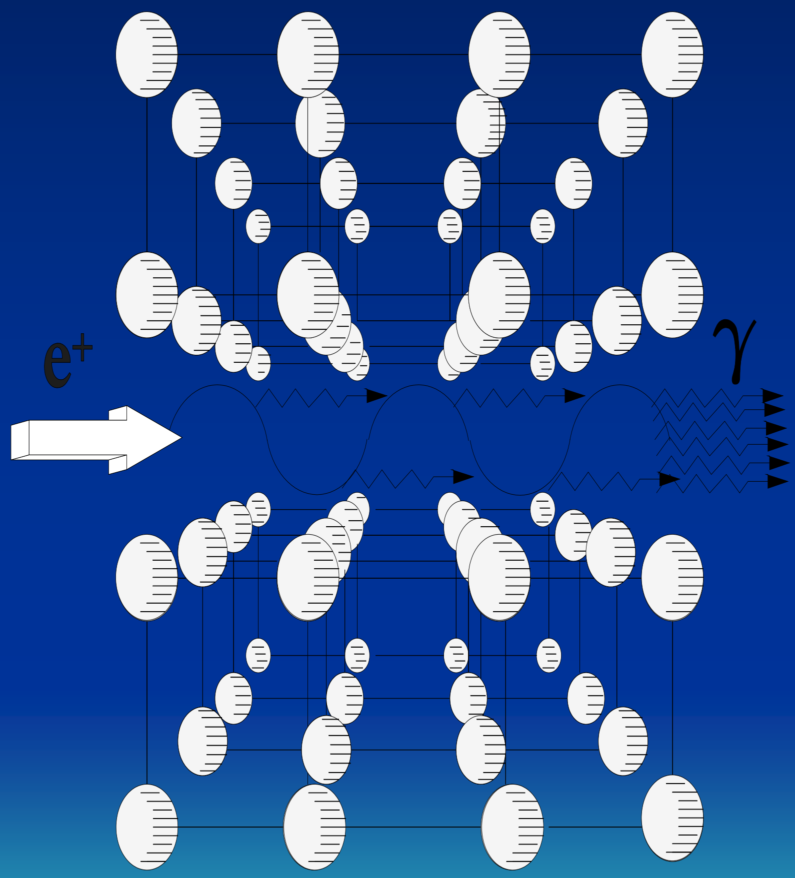
X-ray photons yield gain under temperature gradient.



The spectra of electrons emission in quartz crystal under acoustic waves (□), and unaffected (•).

PXR intensity increases ~ 2-3 times Under the temperature gradient and extenal ultrasonic wave the

Channeling radiation



Strong candidate for the application of small electron accelerators in many fields of science and applied physics. In medical physics monochromatic and tunable radiation offers the possibility of monochromatic X-ray imaging with the advantages of reducing dose and improving the contrast of image. Channeling radiation is energetic, bright and tunable, and has narrow line width in the spectral peaks.