wavelength, and $\gamma = E_0/m$ the Lorentz contraction factor in the rest system of the electron.

Fig. 1 shows the optimal angle θ^{opt} of the crystallographic axis of the SOS aligned crystal with the beam as a function of electron energy for which a CB peak is predicted at $E_\gamma = 0.7E_0$ by equation (2). By changing the angle θ of the crystallographic axis with the electron beam, the position of the hard photon peak can be varied. With the appropriate choice of θ the intensity of the SOS radiation may exceed the Bethe Heitler radiation by an order of magnitude.

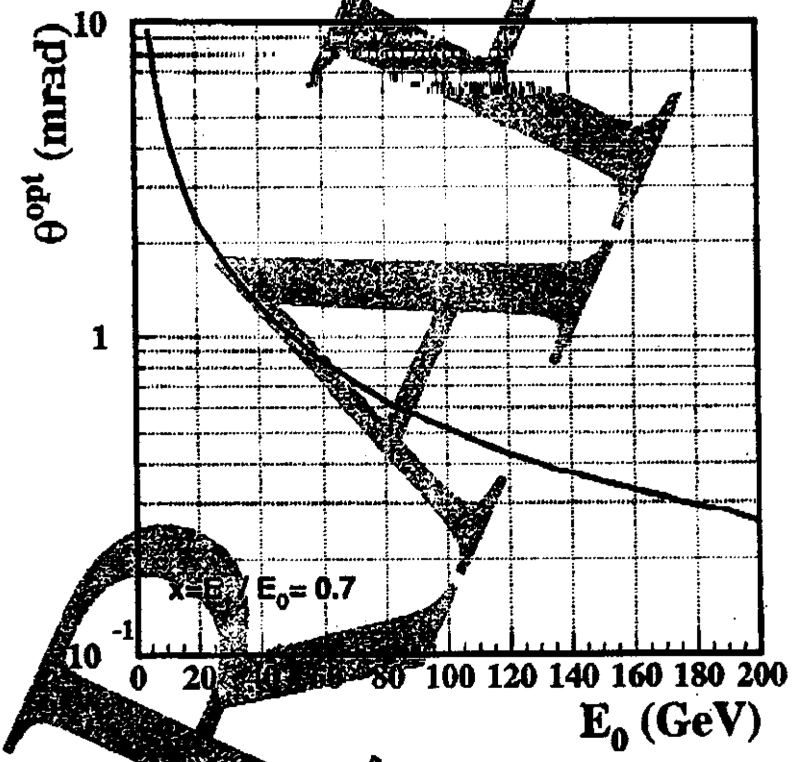

FIG. 1: Optimal angle θ_{opt} between the electron direction in the (110) plane and the ⟨100⟩ axis of the silicon crystal as a function of electron energy E_0. The desired radiated photon energy is $E_\gamma = 0.7E_0$.

The radiation spectrum with the crystal aligned in SOS orientation has in addition to the CB radiation a strong component at low frequency which is characteristic for channelling radiation. As the electron direction lines up with a crystallographic plane in the SOS orientation, the planar channelling condition is fulfilled. For channelling radiation the coherent length is much longer than the interatomic distances and the long range motion, characteristic for planar channelling electrons, becomes dominant over short range variations with the emission of low energy photons. Theoretical calculations predict a more intense soft photon contribution with a high degree of linear polarization of up to 70%.

In this experiment we used a 1.5 cm thick Si crystal in SOS orientation. The 178 GeV electron beam had an angle of $\theta = 0.3$ mrad to the crystal [illegible] (100) axis and was directed along the (110) plane. The high energy peak in the CB [illegible] spectrum is expected at a photon energy of $E_\gamma = 125$ GeV (see Fig. 1). Under this condition the radiation is expected to be enhanced by about a factor 20 with respect to the Bethe-Heitler prediction for a randomly oriented crystalline Si target.

III. EXPERIMENTAL SETUP

The NA59 experiment was performed in the North Area of the CERN SPS, where unpolarized electron beams with energies above 100 GeV are available. We used a beam of 178 GeV electrons with angular divergence of $\sigma_{x'} = 48$ μrad and $\sigma_{y'} = 35$ μrad in the horizontal and vertical plane, respectively.

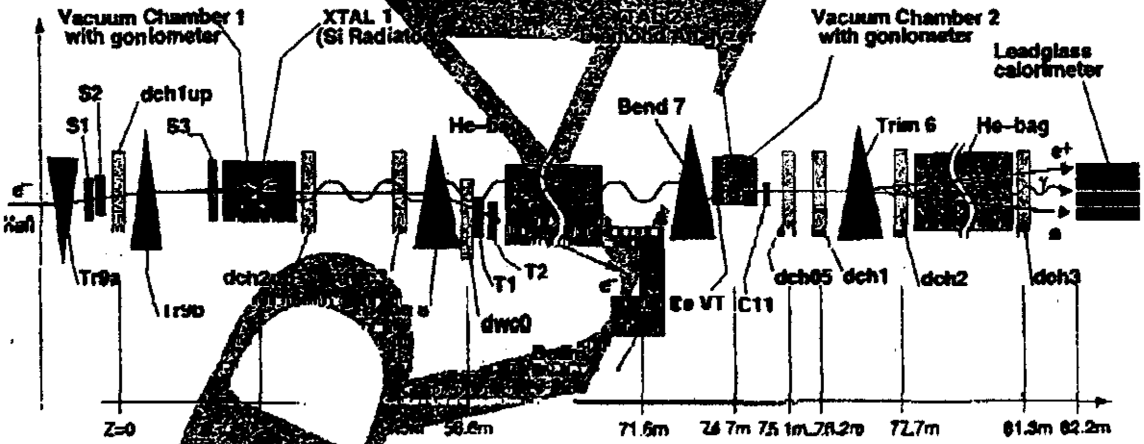

FIG. 2: NA59 experimental setup.

The experimental setup shown in Fig. 2 was also used to investigate the linear polarization of coherent bremsstrahlung (CB) and birefringence in aligned single crystals [7, 8]. This setup is ideally suited for detailed studies of the photon radiation and pair production processes in aligned crystals.

The main components of the experimental setup are: two goniometers with crystals mounted inside vacuum chambers, a pair spectrometer, a segmented leadglass calorimeter, wire chambers and plastic scintillators. In more detail a 1.5 cm thick Si crystal can be rotated in the first goniometer with 2 μrad precision and serves as radiator. A multi-tile synthetic diamond crystal on the ~~first~~ second goniometer can be rotated with 20 μrad precision and is used as the analyzer of the linear polarization of the photon beam. 2

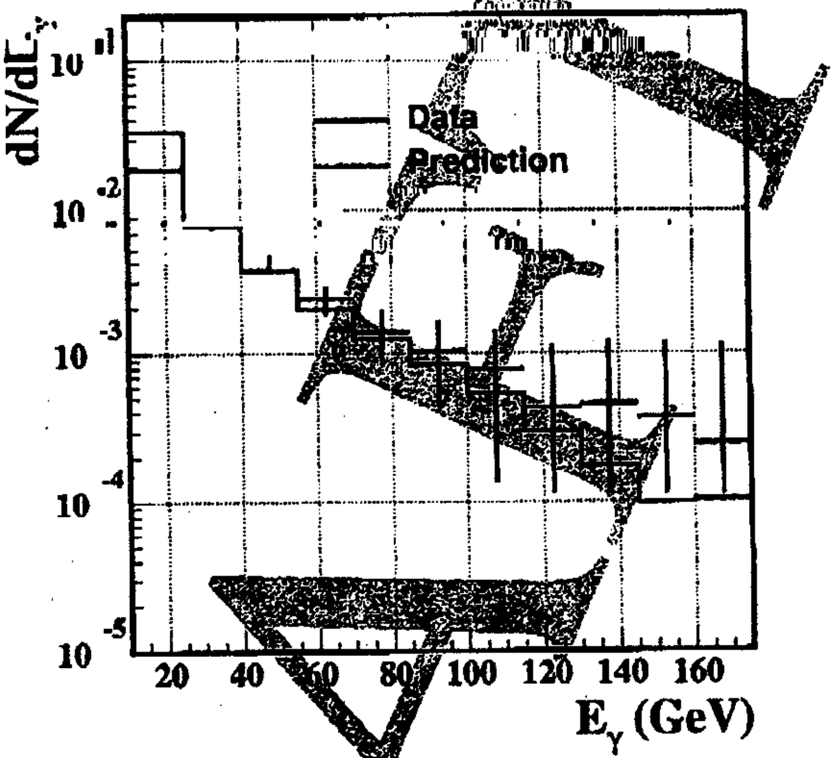

FIG. 3: Probability (dN/dE_γ) of photon emission as a function of the photon energy E_γ in the SOS-aligned Si crystal [illegible] electron of 178 GeV. The black crosses are the measurements and the red histogram represent the MC prediction.

For the chosen SOS orientation of the 1.5 cm thick Si crystal, the most probable radiative energy loss of the [illegible] GeV electrons is expected to be about 80%. The number of photons emitted by an electron that crosses the crystal is high with an average multiplicity ≥ 15, due to a large amount of low energy photons. Under these conditions a high energy photon (i.e. of 125 [illegible] be emitted along the first part of the trajectory of an electron through the crystal, while soft photons will be emitted along the full length of it. Clearly, many electrons pass through the crystal and emit only soft photons.

We see that the expected SOS photon spectrum shows a smoothly decreasing distribution in Fig. 3. The low energy region of the photon spectrum is saturated, due to the abundant production of low energy photons. Above 25 GeV there is satisfactory agreement between the [illegible] photon spectrum (MC simulation) and the data measured with the pair spectrometer.

Fig. 4 shows the total radiated energy by the electrons that passed through the Si crystal. The peak of radiated energy is situated at 150 GeV, which means that each electron lost

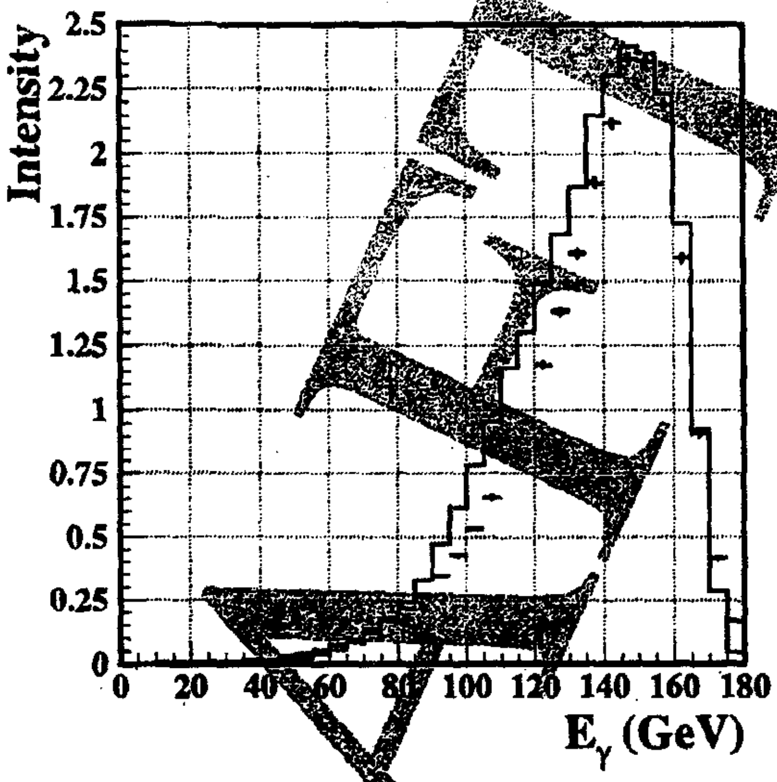

FIG. 4: Intensity of radiation $(dN/dE_\gamma \times E_\gamma^{tot})$ as a function of the total radiated energy E_γ^{tot} in the SOS-aligned Si cr[illegible] GeV electrons. The black crosses are the measurements and the red histogram represent the MC prediction.

about 80% of its initial energy [illegible] the large thickness of the radiator. This means that the effective radiation [illegible] the oriented single crystal is several times shorter in comparison with the amorphous target [illegible] electrons lost practically all their energy in the initial part of the trajectory after passing [illegible] crystal.

The en[illegible] the emission probability compared to the Bethe-Heitler prediction is given [illegible] Fig. 5 as a [illegible] of the total radiated energy. In the energy range of 140 to 160 GeV the enhancement [illegible] factor of 18. The low energy region is depleted due to the large number of photons.

[illegible] expected linear polarization is shown in Fig. 6 as a function of photon energy. It is well [illegible] channeling radiation in single crystals is linearly polarized and the low energy photons [illegible] GeV are also predicted to be linearly polarized in the MC simulations. High energy photons [illegible] predicted with an insignificant polarization.

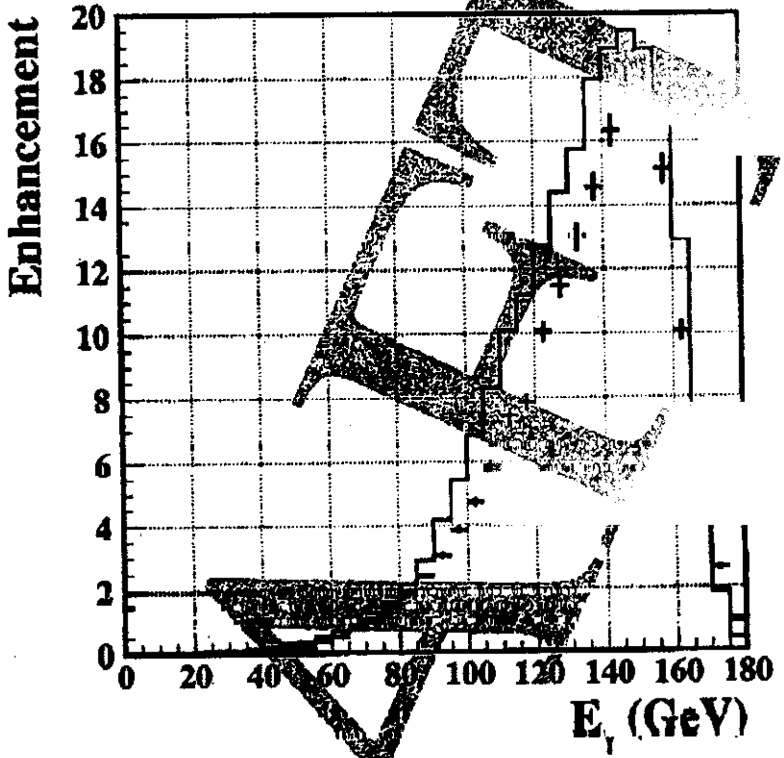

FIG. 5: Enhancement of the intensity with respect [illegible] Bethe-Heitler prediction for randomly oriented polycristalline [illegible] function of the total radiated energy E_γ^{tot} in the SOS-aligned Si crystal by 178 GeV electrons. The black crosses are the measurements and the red histogram represent the MC prediction.

B. Asymmetry Measurement

In this work, the photon po[illegible] is always expressed using the Stoke's parametrization with the [illegible] convention, where the total elliptical polarization is decomposed into two independent linear components and a circular component. In mathematical terms, one writes:

$$P_{\text{linear}} = \sqrt{\eta_1^2 + \eta_3^2} \quad P_{\text{circular}} = \sqrt{\eta_2^2} \quad P_{\text{total}} = \sqrt{P_{\text{linear}}^2 + P_{\text{circular}}^2} \tag{2}$$

The [illegible] angular settings were chosen to have the total linear polarization from the SOS radiation [illegible] η_3, that is $\eta_1 = 0$. The η_2 component is also zero because the electron beam is unpolarized. The expected η_3 component of the polarization shown is in Fig. 6.

In order to determine the linear polarization of the photon beam the method proposed in reference [15] with an oriented crystal was chosen. This method of measurement of the linear polarization of high energy photons is based on coherent e^+e^- pair production (CCP)

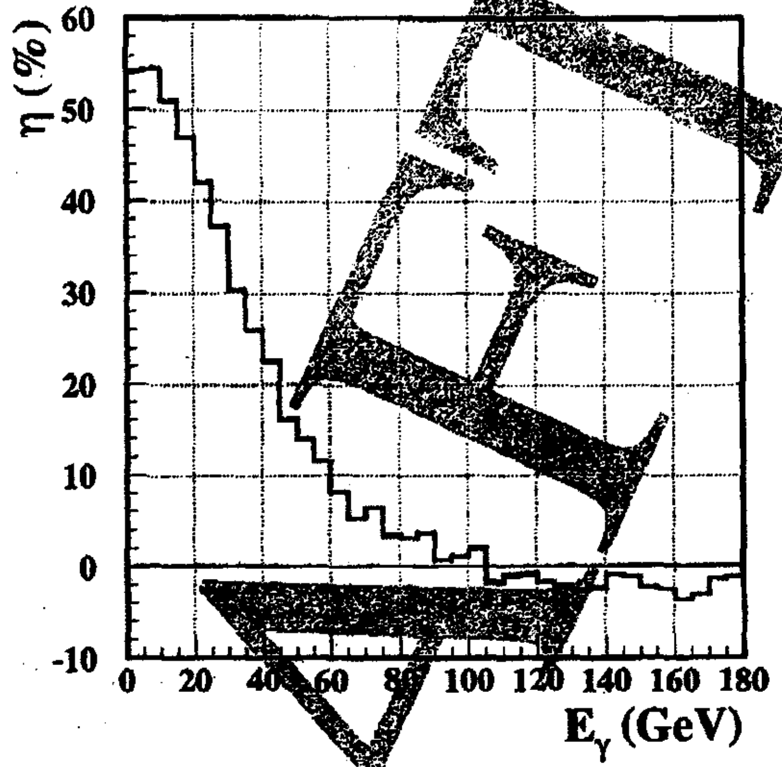

FIG. 6: Expected linear polarization as a function of the energy E_γ of the photons produced in the COC-aligned Si [illegible] GeV electrons.

in single crystals which depends on the orientation of the reciprocal lattice vector and the linear polarization vector. Thus the dependence of the CCP cross section on the linear polarization of the photon beam makes an oriented single crystal suitable as an efficient polarimeter for high energy photons.

The basic characteristic of the polarimeter is the analyzing power R of the analyzer crystall [15]. By choosing the appropriate crystal type and its orientation a maximal analyzing power can be obtained. The relevant experimental quantity is the asymmetry A of the cross sections $\sigma(\gamma \rightarrow e^+e^-)$ for parallel and perpendicular polarization, where the polarization direction is defined with respect to a particular crystallographic plane of the *analyzer* crystal. This asymmetry is related to the linear polarization of the photon beam, P_l, through:

$$A \equiv \frac{\sigma(\gamma_\perp \rightarrow e^+e^-) - \sigma(\gamma_\parallel \rightarrow e^+e^-)}{\sigma(\gamma_\perp \rightarrow e^+e^-) + \sigma(\gamma_\parallel \rightarrow e^+e^-)} = R \times P_l. \quad (3)$$

The analyzing power R corresponds to the asymmetry expected for photons that are 100% linearly polarized perpendicular to the chosen crystallographic plane.

The existence of a strong anisotropy for the channeling of the e^+e^- pairs during their

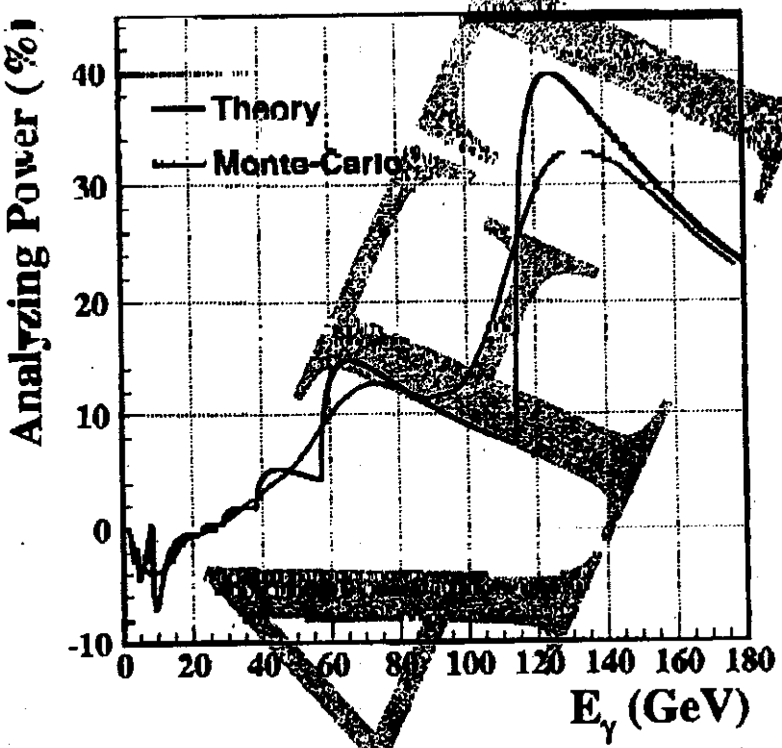

FIG. 7: Analyzing power R with the aligned diamond crystal as a function of the photon energy E_γ (black curve) for [illegible] photon beam without angular divergence and (red curve) for the Monte Carlo cimulation of photons with the beam conditions in the NA59 experiment.

CONCLUSION

Our experimental results show that the high energy photons emitted by electrons passing through our Si crystal radiator oriented in the SOS mode have a linear polarization smaller than 5% at a [illegible] level of 0.9. Earlier results by NA43 indicated that a large polarization could be obtained for high energy photons emitted by SOS oriented single crystals. These promising results for the production of highly polarized high energy photons are not confirmed in our experiment.

Note, that recent calculations also predict that the linear polarization of high energy photons emitted in SOS orientation of the crystal is small compared to the polarization obtained with [illegible] orientation of the crystal. Photon emission by electrons traversing single crystals oriented in the SOS orientation has interesting peculiarities since three different radiation processes are involved: (1) Incoherent bremsstrahlung due to the electron scattering on potential fluctuations due to individual atoms. (2) Channelling radiation induced by the

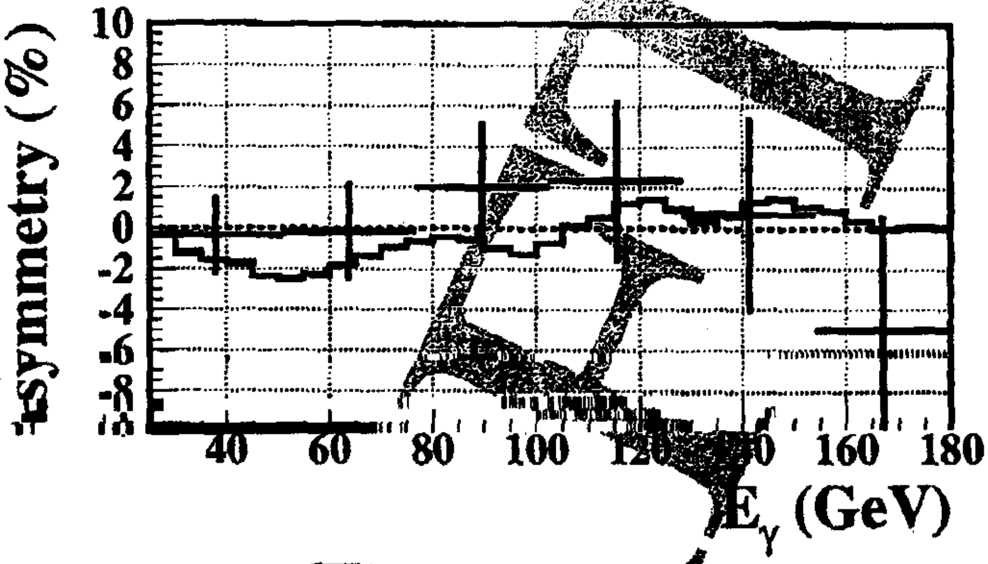

FIG. 8: **Asymmetry of the e^+e^- pair production in the aligned diamond crystal as a function of the** ***photon energy E_γ which is measured to determine the P_1 component of the photon polarization in*** **the SOS-aligned Si crystal by 178 GeV electrons. The black crosses are the measurements and the red histogram represent the MC prediction.**

transverse potential as the electron channels in between crystallographic planes. (3) Coherent bremsstrahlung (CB) induced by the longitudinal variation of the potential due to the periodic structure of the atomic strings in the crystal that are crossed by the electron. The recent calculations have taken [illegible] processes into account.

Since the electron experiences both the transverse potential (channelling radiation) and the longitudinal potential (CB), the spectrum of the emitted radiation should show frequency components characteristic to both phenomena along with possible mixed frequencies. The low energy peak of the radiation spectrum is identified in the MC simulations to the channelling radiation with [illegible] linear polarization and the high energy peak corresponds to the coherent bremsstrahlung (CB) with negligible linear polarization.

Acknowledgments

We dedicate this work to the memory of Friedel Sellschop. We express our gratitude to CNRS, *Grenoble for the crystal alignment and Messers DeBeers Corporation for providing* the high quality synthetic diamonds. We are grateful for the help and support of N. Doble, K. Elsener and H. Wahl. It is a pleasure to thank the technical staff of the participat-