Crystal Channeling Radiation and Volume Reflection Experiments at SLAC

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With the anticipated FACET start-up at SLAC in March 2011, we are studying the feasibility of two related crystal experiments:

- Physics of volume reflection (VR) by e- and e+ in crystals.
  - This will test the standard continuum model of VR for light particles of both charge signs
  - Explore the harmful effects of multiple scattering on VR
  - Possible application of VR to beam halo cleaning in Linear Colliders

- Physics of volume reflection radiation by e- and e+ in crystals.
  - This will test the radiation models for channeled light particles in the regime where “undulator parameter” $K = E/m \cdot \text{deflection angle} \approx 1$
  - Explore possible applications of VR as a new photon source and an energy degrader/collimator for halo particles in colliders
FACET: Facility for Advanced Accelerator Experimental Tests

23 GeV e-, March 2011 (e+ later)

Uncompressed beam:
\[ \Delta p/p < 5 \times 10^{-3} \text{ FW, } \sigma_z > 40 \mu m \]

\[ \varepsilon_n = 30 \text{ mm mrad} \]
\[ \sigma_\theta = 100 \mu \text{rad at } 10\mu \text{m spot} \]
\[ \sigma_\theta = 10 \mu \text{rad at } 100\mu \text{m} \]

For Si at 23 GeV
\[ \theta_c = 44 \mu \text{rad} \]

FACET beam is just right as crystal channeling probe
Bent crystal and volume reflection

- The wiggle periods are smaller further away from the reflection point
- The amplitude of the wiggles diminishes with the distance from the reflection point

Critical channeling angle:

\[ \theta_c = \sqrt{\frac{2U_{\text{max}}}{pv}} \]  \quad (Particle with KE = \frac{1}{2} pv\theta_c^2 = \text{max potential})

VR angle:

\[ \theta_r \approx 2\sqrt{\frac{2U(d_p/2)}{pv}} = 2\theta_c \]
Effects in bent crystals: New experimental work may lead to useful applications!

Deflection Angle of Protons after passing the crystal vs Crystal Rotation Angle.
Data plot from Walter Scandale et al

1 - “amorphous” orientation
2 - channeling
3 - de-channeling
4 - volume capture
5 - volume reflection
Light charged particles: Volume Reflection Radiation

Volume reflection radiation of 200 GeV $e^+$ or $e^-$ on 0.6 mm Si crystal ($R_{\text{bend}} = 10 \text{ m}$)

Yu. Chesnokov et al, IHEP 2007-16

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(amorphous brems)

Scaling $E_\gamma$ with $E$: $\sim E^{3/2}$ for $E << 10 \text{ GeV}$ and $E^2$ for $E >> 10 \text{ GeV}$ (Gennady Stupakov)

VR radiation is very similar for both $e^+$ and $e^-$, and has large angular acceptance – it makes this phenomena good candidate for collimation system of linear collider.
LC Collimation concept based on VR radiation
A. Seryi et al

e- or e+ beam

Beam

halo

VR halo particles with dE/E~20% loss due to VR radiation

photons of VR radiation (to be absorbed in dedicated places)

Absorb off-Energy particles

Crystal with Volume Reflection

Bends
Volume Reflection angles: Igor Yazynin’s codes
Example: 400 GeV protons, Si(110), crystal \( R = 10 \text{ m} \), length=1mm

“Rotation Angle” - crystal orientation rel. to beam initial direction

“Angular Profile” - change in particle angle relative to initial beam direction

Max crystal angle for VR to occur = crystal thickness / \( R \)
23 GeV: $\theta_{c0} (\sim E^{-1/2}) = 0.044 \text{ mrad}, \ R_{\text{crit}} (\sim E) = 0.05 \text{ m, } L_{\text{dech}} (\sim E) = 0.75 \text{ mm}$
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OBSERVATION OF RADIATION
FROM 10 GEV POSITRONS AT VOLUME REFLECTION
IN BENT SILICON MONOCRYSTAL

Figure 1. Scheme of volume reflection process in bent single crystals.

Figure 2. Behaviour of the transversal particle velocity (divided on c) as a function of time (in femtoseconds). (Time t=0 corresponds to enter point in single crystal.)
OBSERVATION OF RADIATION
FROM 10 GEV POSITRONS AT VOLUME REFLECTION
IN BENT SILICON MONOCRystal

2. Experimental setup

Experiment was carried out on 22 beam line of IHEP accelerator. Fig. 3 illustrates the experimental layout.

- Quads
- Lead glass calorimeter
- BGO crystal calorimeter
- S = scintillators
- 0.65 mm thick Si
- R=1.3 m
- dipole
- hodoscope
10 GeV e+

Photon energy spectrum prominent at ~100 MeV. Scales as $\gamma^{3/2}$.

At 23 GeV, we would expect this spectrum to shift >200 MeV.

Figure 5. The coherent part of $\gamma$-quanta spectrum (a) and corresponding energy losses of positrons (b) in silicon single crystal. Points are experiment and solid line is calculation. The dashed curve is calculated energy losses in nonoriented single crystal.
23 GeV e- & e+ VR radiation at FACET

- A possible FACET experiment would be a collaboration in which we use the IHEP-NPI Si crystal (if available) from their 10 GeV experiment.

- VR radiation experiment at FACET would first involve e- and in the future e+, both at 23 GeV.

- The FACET results could be compared to the 10 GeV positron IHEP-NPI results for the same crystal.

- IHEP colleagues have a detailed VR radiation code and next step would be to collaborate on some detailed radiation calculations for planned FACET beams.

- At present we use a simple wiggler model of Gennady Stupakov for estimating VR spectrum.
Potential energy in crystal

Channeling in a crystal is similar to motion in a wiggler—the transverse oscillations are confined by the potential energy $U$. I assume that the oscillations are at the energy $U_{\text{max}}/2 \approx 10$ eV, with the amplitude $x_0 \approx 0.7$ Angstrom. Then

$$\psi_0 = \sqrt{U_{\text{max}}/E}.$$ 

We also have

$$k_w = \psi_0 / x_0.$$  

Scalings: $\psi_0, k_w \propto 1/\sqrt{\gamma}$ and $K \propto \sqrt{\gamma}$. One can compute all parameters of the wiggler motion and the corresponding radiation.

FIG. 2. One-dimensional potential (a) and electric field (b) in the (110) plane of a silicon single crystal (at the room temperature), as functions of the relative coordinate $x/d$, where $d = 1.92 \text{ Å}$ is the interplanar distance. Curves 1 and 2 correspond to calculations based on the atomic form factors from x-ray measurements and the Moliere model.
For 23 GeV particle in Si channel:

\[ \lambda_w = \text{period of the sinusoidal orbit} = 14.3 \text{ micron} \]
\[ k_w = \frac{2\pi}{\lambda_w} = 0.44 / \text{micron} \]
\[ \psi_0 = \text{max (amplitude) deflection angle} = 29.5 \text{ micro-radian} \]
\[ x_0 = \frac{\psi_0}{k_w} = \text{amplitude of the deviation} = 0.672 \text{ angstrom} \]
\[ K = \gamma \psi_0 = 1.33 \]

VR radiation intensity is determined by effective number of wiggles. In the range 10 – 200 GeV, most of the radiation comes from 10-20 wiggles.
Spectrum of the wiggler radiation

Figure: $K = 1$ (10 GeV)

Figure: $K = 4$ (200 GeV)

The frequency

for 23 GeV ($K=1.33$): \[ \omega_0 = \frac{2\gamma^2 c k w}{1 + K^2/2}. \]

= $2.83\times10^{23}$ /sec or 187 MeV

The vertical axis is the radiated energy $E$ per unit frequency range $E_{\gamma} = h\omega$ of the photon spectra per unit period of the wiggler. For large $K \gg 1$, the spectrum extends to $\omega \sim \omega_0 K^3$. 

16
Wiggler Model Estimate of 23 GeV e- VR Radiation

Predict substantial radiation in the 200-600 MeV range

strong spikes are artifice of exactly periodic motion in this model - expect it to be smoothed by variable periodicity of wiggles

G. Stupakov

23 GeV e-
K = 1.33
20 wiggles

amorphous bremst
Summary

1. We have begun a study of possible VR physics and radiation experiments at the planned FACET facility of SLAC, with beam expected in March 2011.

2. FACET 23 GeV e- and e+ beams will have $\theta_{\text{rms}} \sim 10\text{-}100 \ \mu\text{rad}$ for 100-10 $\mu\text{m}$ spot sizes, well-matched to the channeling critical angle in Si, and a good probe for VR effects.

3. If we use the IHEP-NPI Si crystal, 0.65 mm thick, $R=1.3$ m, the VR angles are about 30 $\mu\text{rad}$, but multiple scattering gives an rms spread of 40 $\mu\text{rad}$. VR angle can still be clearly identified from the distributions.

4. The VR radiation spectrum for this case is estimated to have photons in the range 200 – 600 MeV using a simple wiggler model, with about 20 channel wiggles providing most of the radiation.
Extra slides
This is a “decision-tree” code, not full Monte Carlo. Yazynin Code includes processes:

- multiple scattering
- channeling
- volume capture
- de-channeling
- volume reflection

Basic approx: Code replaces details of particle orbits with Monte Carlo fits based on distribution fcns and analytic formulas for trajectories over long distances (not on scale of betatron motion in bent crystal). It applies probabilities to dechanneling, volume capture, volume reflection, amorphous transport, Coulomb and nucl scattering angles, energy loss, etc. Both proton and electron versions of code exist.
VR rms = 1.2E-2 mrad
(Multiple Scattering is main contribution)

VR angle = -1.4E-2 mrad

Code VR: \( \theta_{\text{refl}} = -0.8 \theta_c \left(1 - 2.55 \left(\frac{R_{\text{crit}}}{R}\right)\right) \)

\( \theta_c \sim E^{-1/2} \quad R_{\text{crit}} \sim E \quad L_{\text{dech}} \sim E \)

(0.02 mrad) (0.21 m) (3 mm)