Crystal Experiments at SLAC FACET and ESTB

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Motivation (deflection)

- Bent crystals can deflect high energy beams with small bending radii ($O(0.1m)$)
  - lots of proton data, little data for high-energy $e^-$ or $e^+$
  - There is interest in crystal collimation for $e^+$ and $e^-$
    - Expected benefits in size and efficiency of collimation
    - Not enough data to actually design such a system
    - Possible application to ILC, LCLS-II
  - What channeling efficiency can one expect?
  - How does it scale with beam energy?
  - Can VR be used for beam collimation?
Motivation (radiation)

- There is interest in channeling radiation
  - Intense $\gamma$ ray production, can we demonstrate narrow-band?
  - Use Crystal undulators with $e^-$ ??
  - Can we make use of VR radiation?
- $\gamma$ rays have applications in materials science and radiography techniques
  - Penetrating $\gamma$ rays can radiograph thick pieces.
  - Crystal targets have been used with some success in $\gamma$ sources for photo-nuclear reactions.
- Can crystal sources become competitive to Compton sources?
Crystal Experiments at SLAC

- **T513 (Wienands et al., ESTB, complete)**
  - Channeling and Volume-Reflection Studies of High-Energy Electrons in Crystals
  - SLAC—U Ferrara—U Aarhus—Cal Poly

- **E212 (U. Uggerhøj et al., FACET)**
  - Radiation from GeV electrons in diamond – with intensities approaching the amplified radiation regime

- **T523 (Wienands et al., ESTB)**
  - γ-Ray Production Study with Electrons
  - SLAC—U Ferrara—U Aarhus—Cal Poly
FACET and the End Station A Test Beam (ESTB)

- ESTB: up to 15 GeV $e^-$, 5 Hz, $\leq 200$ pC/pulse
  - “pulse stealing” from LCLS
- FACET: 20 GeV $e^+$ or $e^-$, 2 nC/pulse, 10 Hz, “$20^3 \mu m^3$”
- control of optics, momentum spread
  - both can provide relatively parallel beam ($<10 \mu$rad)
  - FACET has a $e^-$ spectrometer downstream; $\approx 0.1\%$ resolution
Main crystal features

- **Crystal thickness 60±1 µm**
  Once the crystal will be back in Ferrara we will measure crystal thickness with accuracy of a few nm.

- **(111) bent planes** (the best planes for channeling of negative particles).

- **Bending angle 402±9 µrad**
  (x-ray measured). If needed I can provide a value with lower uncertainty.
Si (111) Potential for T513 Crystal ($\rho = 0.15$ m)

$$\theta_{\text{crit}} = \sqrt{2U_0/E} \approx 80 \mu r \ @ \ 6.3 \text{ GeV}$$
Crystal mounted in “Kraken” Chamber in ESA
Crystal-Rotation @ 4.2 GeV

(Movie credit: T. Wistisen)
Triangle Plots

Colors rep. log(intensity).
Crystal angles from fit to laser spot (est’ d uncertainty 2…5 µrad)
Dechanneling Length of $e^-$


$L_D = 15.3 \frac{\mu m}{GeV} E[GeV] \left( 1 - 1.76 \frac{2R_c}{R} \right)$
Volume Reflection Angle


\[ \theta_{VR} = 338 \, \mu\text{rad} \cdot E[\text{GeV}]^{-0.81} \]

\[ \theta_{VR} = 207 \, \mu\text{rad} \cdot E[\text{GeV}]^{-0.5} \]

Data
Fit 1
Fit 2
Scattering in “Free” Direction


\[
\sigma_{MS} \ [\mu \text{rad}]
\]

\[
E \ [\text{GeV}]
\]

Data
Fit 1

mult. scatt.
E212: First Channeling Data of 20 GeV $e^+$ in Bent Crystal

- **Raw data**


20.35 GeV $e^+$
$10^{10} e^+/pulse$

e$^-$ data, 20.35 GeV, $10^{10} e^-/pulse$
Analysis of the "Quasi-Channeling Oscillations"

R. Mikkelsen et al., in prep.

\[
\theta_{\text{def}} = (\theta_b + \theta_t) - \sqrt{\frac{2d_0(n-1)}{R} + \frac{2d_s}{R}}
\]

\[\theta_b = 402\pm9 \mu \text{rad}, \quad R = 0.15 \text{ m}, \quad d_s = 3.14\text{Å} \text{ (known), } d_0 = 4 \, d_s\]

\[R = 15\pm1.3 \text{ cm} \quad \theta_t = 40 \mu \text{rad}\]
Summary of Deflection Results

- Channeling efficiency ≈ 18...24 %, VR up to 95%
- Dechanneling length ≈ 40...60 µm
  - independent of the beam energy
- Surface transmission 57% (6.3 GeV)...65% (3.35 GeV)
  - calc: 57% @ 6.3 GeV
- Scattering is enhanced in the vertical plane for channeled particles
  - by roughly a factor 2 (X₀ → X₀/4)
- Quasi-Channeling oscillations observed with e⁺
  (and hints with e⁻).
Monolithic Undulator

Large amplitude, long period (LALP, Solov’yov et al.):

Small amplitude, short period (SASP, Kostyuk 2014):

“Slow” betatron oscillations, fast undulations
- 37 μm long, 120 periods, (110)
- 0.7 GeV @ 6.2 GeV $e^-$
- 4 GeV @ 16.1 GeV $e^-$
- $K \approx 0.07$

Si$_{1-x}$Ge$_x$-graded composition
Overview

High-frequency wiggles can produce undulator radiation (logitudinally coherent)

Zoom-in
Expected spectra, 16 GeV

Note: Spectral feature mostly from over-the-barrier motion as $R_{\text{wig}} < R_c$
Aarhus Monolithic Undulator

- 37 µm thick; 120 periods.
T513/T523 Experiment Layout (ESTB)

Top View, not to scale


8 mm slit collimator

Side view of YAG screen

Beam axis

Screen

Vertical bend mag.

Wire scanner

Ce:YAG screen

Collimator scanner

8 mm slit collimator

Counter

Wall

Beam axis

CCD camera

Screen

Diagram of the experimental setup with labels for various components and distances.
Crystal Alignment with Full Beam

Approximately 2 mr FWHM

Mean Sci-fi Bin vs. Ruler Position

5 mr
Angular Distribution Aligned – Amorph

Pulse height difference (pC/electron)

$X_{SciFi}$ (mm)

SciFi acceptance

8 mm
160 µm
200 µm

U. Wienands – Channeling 2016, Desenzano di Garda

Argonne National Laboratory

U. Wienands – Channeling 2016, Desenzano di Garda

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E212/T523 Summary

- Gamma rays detected from the crystals
  - In 2015 we saw evidence for channeling and VR gamma rays from the Ferrara bent Crystal (60 µm, 400 µrad, 0.15 m)
  - Gamma rays from 37-µm Aarhus Undulator seen this summer

- Clearest signals in intensity distributions
  - VR radiation from Ferrara crystal
  - Channeling radiation from Aarhus undulator
  - Signal/background ratio 1:1 -> 1:4

- Energy spectra have been difficult to acquire.
Beyond T523 and E212

- Continuing focus on radiation experiments
- Possibly explore lower beam energies
  - ESTB will go off-line soon for LCLS-II installation.
  - FACET is off-line now for the same reason.
  - ESTB to be reconnected to the linac mid-2017;
    - resume operation July...Oct. 2017; until June 2018
    - then down a year for LCLS-II install., back up July 2019.
    - same beam parameters as now.
- Potential competition by DASEL proposal for a Dark Matter experiment.
Planning for FACET-II as a Community Resource

- FACET stopped running in April 2016 to begin LCLS-II construction
- Over the next few years FACET-II will add new capabilities:
  - LCLS style photoinjector with state of the art electron beam
  - Flexibility e.g. low-charge mode or ‘two color’ operation for two-bunch PWFA
  - Nominal $e^-$ parameters: 10GeV, 2nC, 15kA, 30Hz (2019)
  - Nominal $e^+$ parameters: 10GeV, 1nC, 6kA, 5Hz (2021)
  - External injection → Staging studies, ultra-bright sources

- Continue to plan experimental program with Science Workshops

SLAC Linac in 2025

FACET-II has been designed to address many of the R&D challenges of the Beam Driven Roadmap
Thank you!