Crystal Channeling Experiments in the USA

U. Wienands (Argonne National Laboratory);

Channeling 2018
Ischia, IT
Channeling Experiments with Electron & Positrons in the USA

- Focusing on the radiation aspect of channeling leptons
  - Miroshnichenko et al., SLAC 1978
    - first > 10 GeV work (with positrons)
- The SLAC experiment sparked interest in the US
  - R.H. Pantell, Stanford, B.L. Berman et al., Livermore, mid-1980s:
    - Channeling radiation, 10s of MeV electrons.
    - Some theoretical notes by S. Heifets (SLAC-PUB-2137 and 2173)
    - Theoretical work by Ellison (UNM) et al. beginning in the 1980s.
- Most experiments done in former USSR.
- Renaissance of interest in the field in the West
  - in light of new, very high-energy electron-positron colliders.
  - in hadron collimation and extraction (FNAL, BNL, CERN).
**Electron Channeling at Fermilab**

- **NIU-FNAL-Vanderbilt-Rossendorf-LANL at HBESL**
  - 4 MeV, ≤ 10 nC e⁻, 10μm (111) Diamond crystal
  - channeling radiation (≈ 1 keV)

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![Diagram](image)
NIU-FNAL-BYU-KU-Sokendai collaboration (at FAST)

- 50 MeV, <100 fC/pulse, 40 μm Diamond crystal, Rossendorf goniometer (from ELBE). X-ray generation, beam collimation
- later, possibly a flat pyrolitic graphite crystal is planned (HOPG)
Resuming Channeling Experiments @ SLAC

- SLAC joined the US-LARP program (LHC Accelerator Research Prog.)
  - Beam collimation one area of LARP interest (for SLAC in ILC context).
  - SLAC, incl. this author, joined the UA9 collaboration of Scandale et al.
- FACET was being commissioned, providing an exp. facility

- SLAC + Aarhus (Uggerhøj) + Ferrara (Mazzolari) + CalPoly (Holtzapple)
  - T513 Collaboration (Channeling & VR, ESTB, e⁻)
  - E212 (Radiation & crystal undulators, FACET, e⁺ and e⁻)
  - T523 (γ-Ray production, ESTB, e⁻)
FACET and the End Station A Test Beam (ESTB) 2011…2016

- 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
Deflection Experiments (T513, ESTB)

- Measurement of channeling parameters of 3...14 GeV $e^-$
  - bent crystal from U. Ferrara
Crystal thickness $60\pm1$ 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 $402\pm9$ µrad, $\rho=0.15$ m (x-ray measured). If needed I can provide a value with lower uncertainty.
Crystal mounted in “Kraken” Chamber in ESA
Crystal-Rotation @ 4.2 GeV

Wienands et al., Physical Review Letters 114, 2015, 074801

(Movie credit: T. Wistisen)

A bending radius of 0.15 m giving a total bending angle of 8.4 μrad.

The crystal deflects particles on the screen is avoided. The crystal deflects particles along the edge of the screen is avoided. The crystal deflects particles.

The camera was rotating the crystal in small angular steps and recording an image of the circular YAG screen. The camera was mounted at an angle with respect to the screen which was known to be circular. This allows distorted the image. An ellipse was fitted along the edge of the screen, for this was known to be circular. This allows.

An image of the circular YAG screen. The camera was rotating the crystal in small angular steps and recording an image of the circular YAG screen. The camera was mounted at an angle with respect to the screen which was known to be circular. This allows distorted the image. An ellipse was fitted along the edge of the screen, for this was known to be circular. This allows.

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Dechanneling Length of $e^-$

T.N. Wistisen et al.,

Channeling efficiency 18…25%
Volume Reflection Angle

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

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

Scattering in “Free” Direction

- MS in channeling is enhanced by \( \approx \) factor 2.
  - expressed in \( X_0 \), it is a factor 1/4.

E212: First Channeling Data of 20 GeV e\(^+\) in Bent Crystal

- **Raw data**

![Raw data image](Image)


E212 Data e\(^+\)

20.35 GeV e\(^+\)

\(10^{10} e^+/pulse\)

e\(^-\) data, 20.35 GeV, \(10^{10} e^-/pulse\)

![Graph](Image)

Probability Density \(dp/d\theta\)

Deflection (mrad)

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Deflection (mrad)

20.35 GeV e\(^+\)

\(10^{10} e^+/pulse\)

e\(^-\) data, 20.35 GeV, \(10^{10} e^-/pulse\)

![Graph](Image)
Analysis of the “Quasi-Channeling Oscillations”


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

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

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

- Channeling efficiency \( \approx 18\ldots24\% \), VR up to 95%
- Dechanneling length \( \approx 40\ldots60\ \mu m \)
  - roughly independent of the beam energy in our range
- 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 (\( X_0 \rightarrow X_0/4 \))
- Quasi-Channeling oscillations observed with \( e^+ \)
  (and hints with \( e^- \)).
  - dechanneling length with electrons approx. 350 \( \mu m \).
VR Collimator Concept

- The T513 data can be used to investigate beam collimation:
- APS-U: 6 GeV, 2 T513 crystals in series
- pdf to generate deflections

![Diagram showing beam deflections and data points](image.png)
Radiation Experiments

- ESTB Setup augmented with $\gamma$ counter and deflector.

Top View, not to scale
High-Intensity spectra

many photons per linac pulse
energy-weighted pulse height spectra of $\Sigma E(\gamma_n)$
Monolithic Undulator

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

- 37 µm long, 120 periods, (110)
- $E_\gamma \approx 0.7$ GeV @ 6.2 GeV $e^-$
- $E_\gamma \approx 4$ GeV@ 16.1 GeV $e^-$
- $K \approx 0.07$

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

“Slow” betatron oscillations, fast undulations

- $Si_{1-x}Ge_x$-graded composition
Expected spectra, 16 GeV

(Wistisen, 2016)

Comparison of spectrum of similar crystal at 855 MeV (MAMI expt., Wistisen et al., PRL 112, 254801 (2014))
Angular Distribution Aligned – Amorph

Undulator crystal angle scan

$\approx 2 \text{ mr FWHM}$

$\gamma$ angle scan
(aligned crystal – amorph)

SciFi acceptance

Of three indicators for undulator radiation
(crystal orientation, directional, energy spectrum),
two have been seen.
T523 and E212 and Beyond

- ESTB & FACET have been off since late 2016
- ESTB is on-line again until end of 2018.
- FACET is off-line until end 2019.
  - $e^-$ only, no $e^+$ until 2022 or 2023

- We will have our next E212/T523 run in November

- A Dark Matter experiment (DASEL) is supporting creation of a GEANT model of the beam line => better understanding of the backgrounds.
- A group from CERN is interested in radiation experiments with W crystals
  - $e^+$ source study for CLIC and/or FCC-ee or ILC
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) → Beam quality
  - Nominal $e^+$ parameters: 10GeV, 1nC, 6kA, 5Hz (2021) → Positron Acceleration
  - External injection → Staging studies, ultra-bright sources
- Continue to plan experimental program with Science Workshops

FACET-II has been designed to address many of the R&D challenges of the Beam Driven Roadmap.
T513/E212/T523 Collaboration

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