Channeling, Volume Reflection and γ-Ray Production by Electrons at Multi-GeV Beam Energy in Crystals

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U.S. DEPARTMENT OF ENERGY

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Motivation

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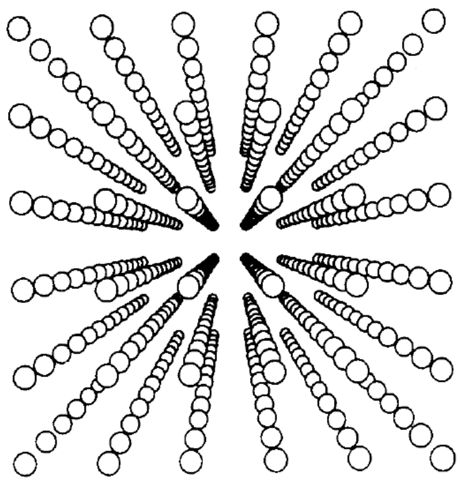
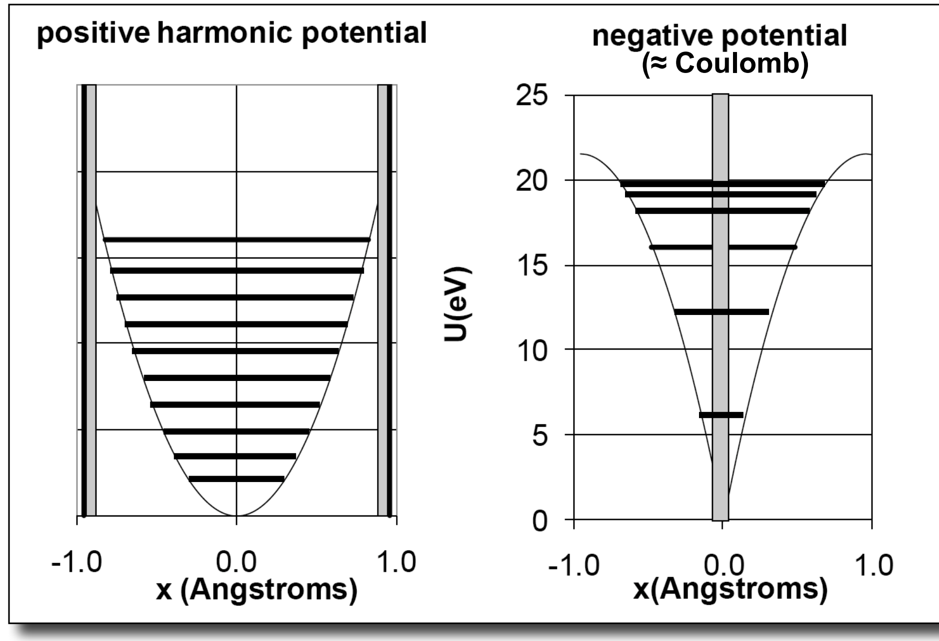
- Bent crystals can deflect high energy beams with small bending radii (O(0.1m))
  - lots of proton data, little data for high-energy e^- or e^+
- There is interest in crystal collimation for e^+ and e^-
  - Expected benefits in size and efficiency of collimation
  - Not enough data to actually design such a system
  - Possible application to ILC, LCLS-II
- There is interest in channeling radiation
  - Intense γ ray production, possibly narrow-band
  - "Crystal undulators" with e^- ??
  - Can we get to significant intensity?
  - Volume-reflection (VR) radiation not well understood

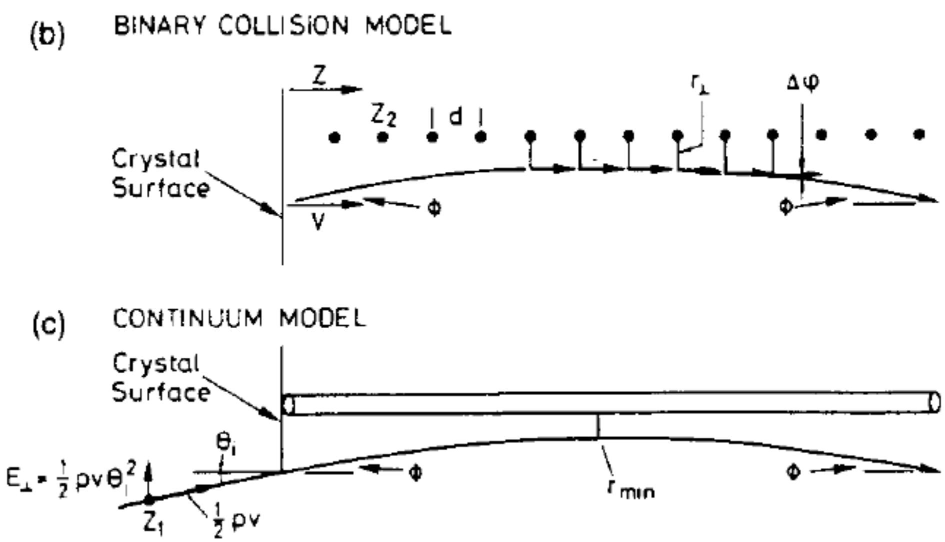
Crystal Experiments at SLAC

- E212 (Uggerhøj et al., FACET)
  - Radiation from GeV electrons in diamond – with intensities approaching the amplified radiation regime
  - U Aarhus—U Ferrara—SLAC—Cal Poly—CERN—U New Mexico—U Frankfurt—U Mainz—U Amsterdam—U Johannesburg
- T513 (Wienands et al., ESTB)
  - Channeling and Volume-Reflection Studies of High-Energy Electrons in Crystals
  - SLAC—U Ferrara—U Aarhus—Cal Poly
- T523 (Wienands et al., ESTB)
  - γ -Ray Production Study with Electrons
  - SLAC—U Ferrara—U Aarhus—Cal Poly

Channeling Potentials







Binary collision: deflection ∑ scatters

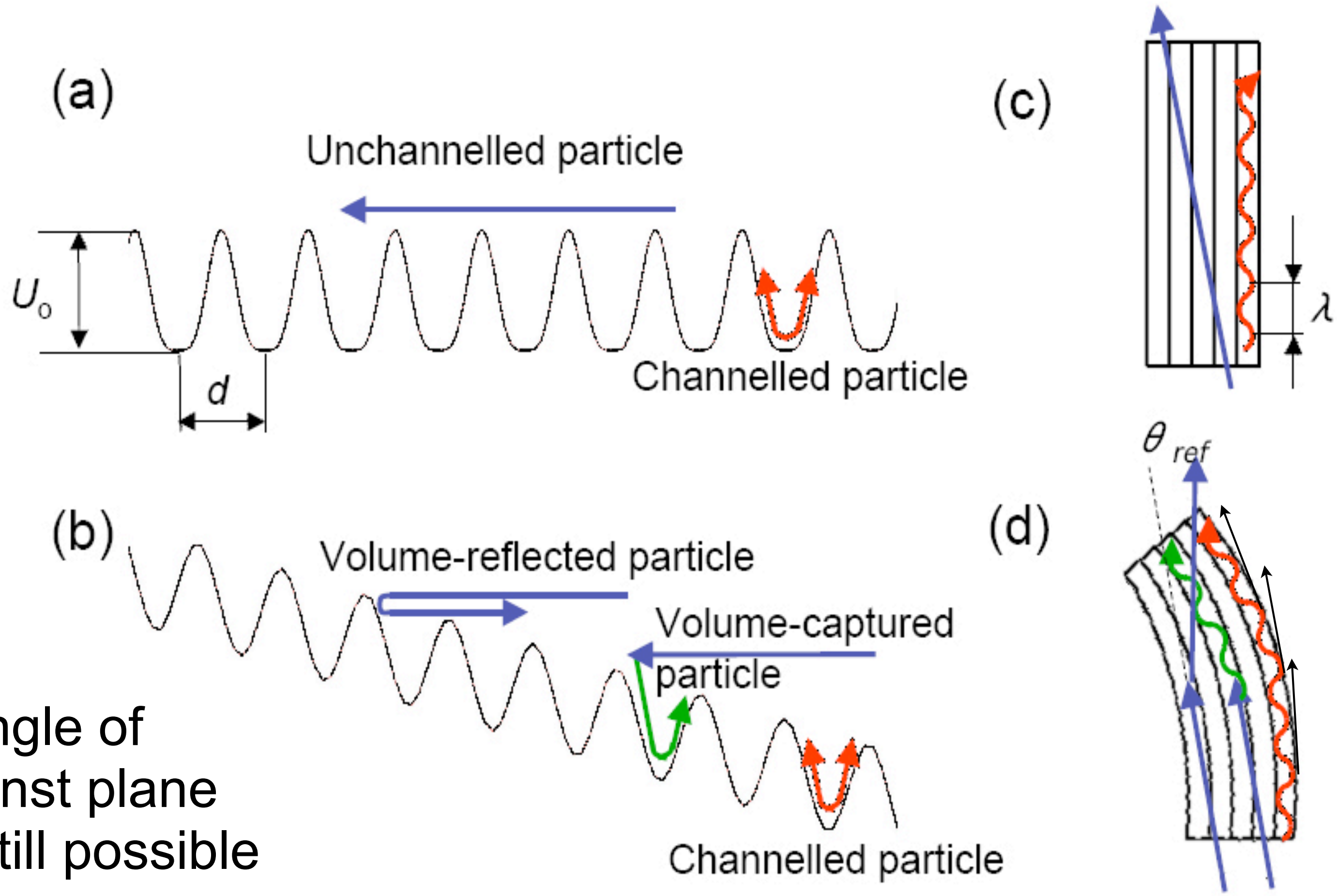
Continuum model: average potential

Particle-Crystal Interaction

W. Scandale (adapted)

Possible processes:

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



Critical angle: max. angle of incoming particle against plane where channeling is still possible

$\theta_{crit} = \sqrt{2U_0/E}$

Dechanneling rate ∝ # in channel => ∝ exp($-s/L_d$); L_d is called *dechanneling length*

Phase Space (bent crystal)

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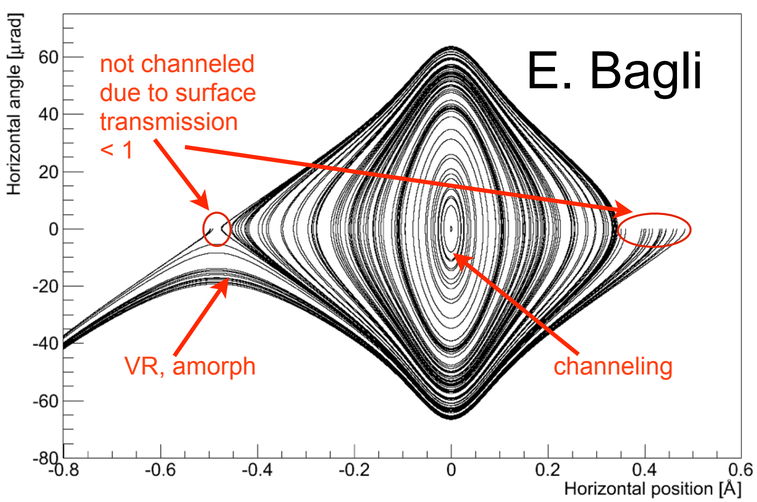
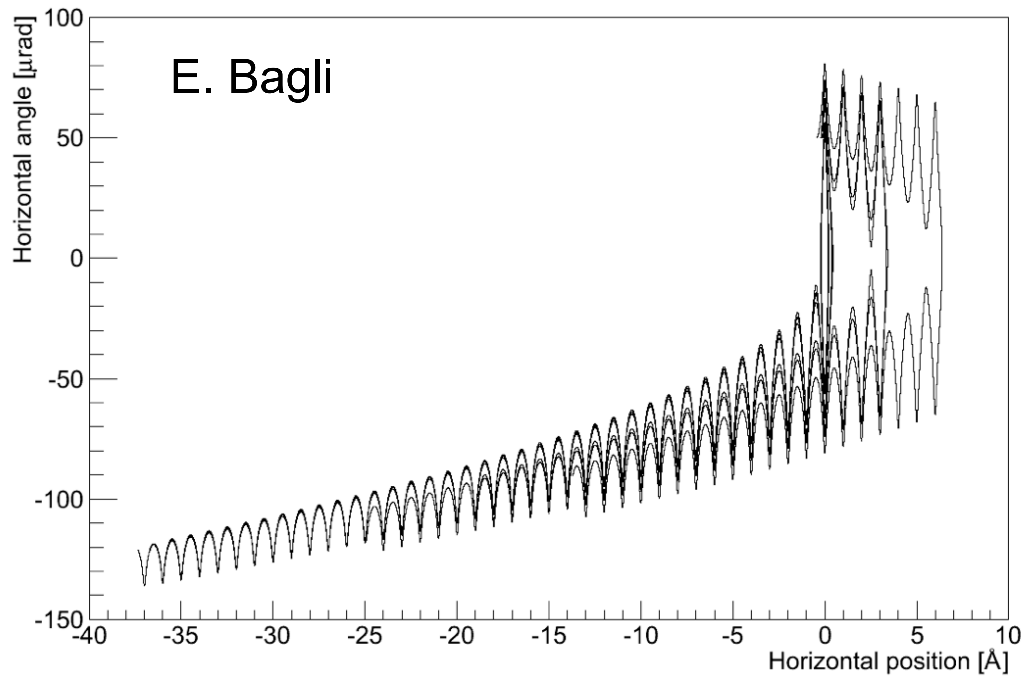
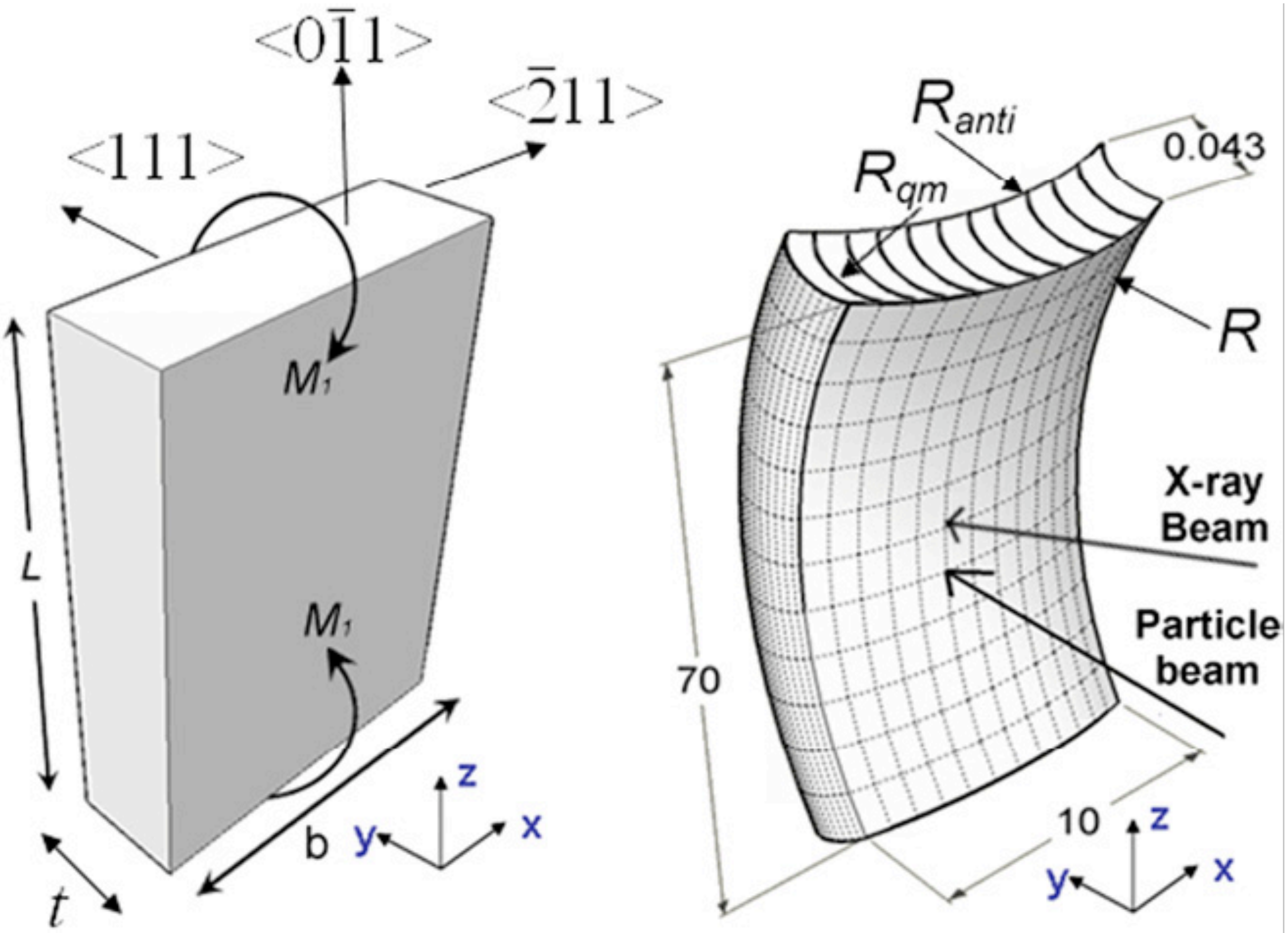
- Same topology as a (stationary or moving) rf bucket



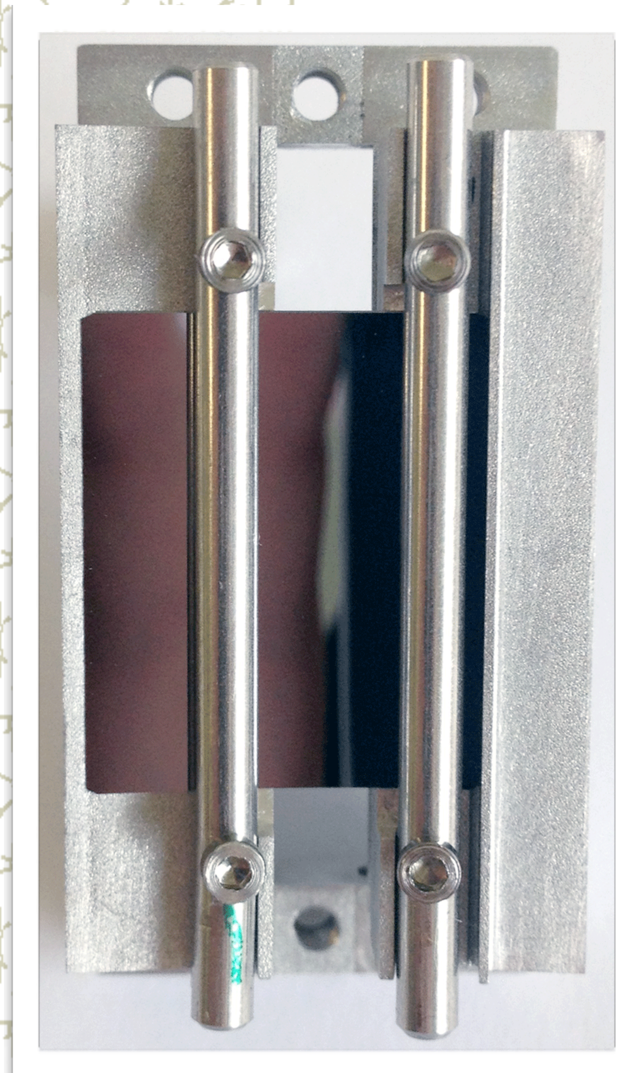


Quasi-Mosaic Crystal

Guidi et al.



Main crystal features



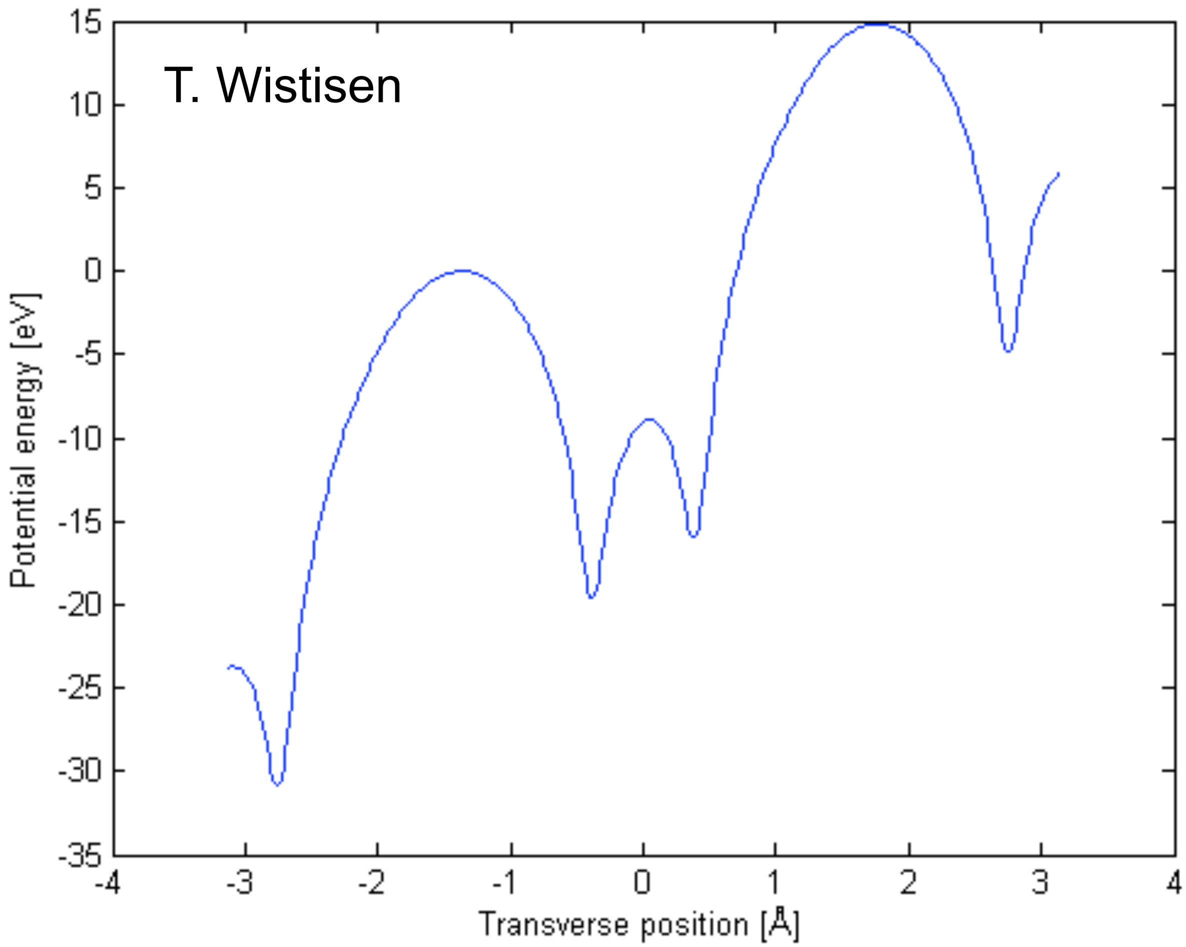
- **Crystal thickness 60±1 μm**
  Once the crystal will be back in Ferrara we will measure crystal thickness with accuracy of a few nm.

- **(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.**

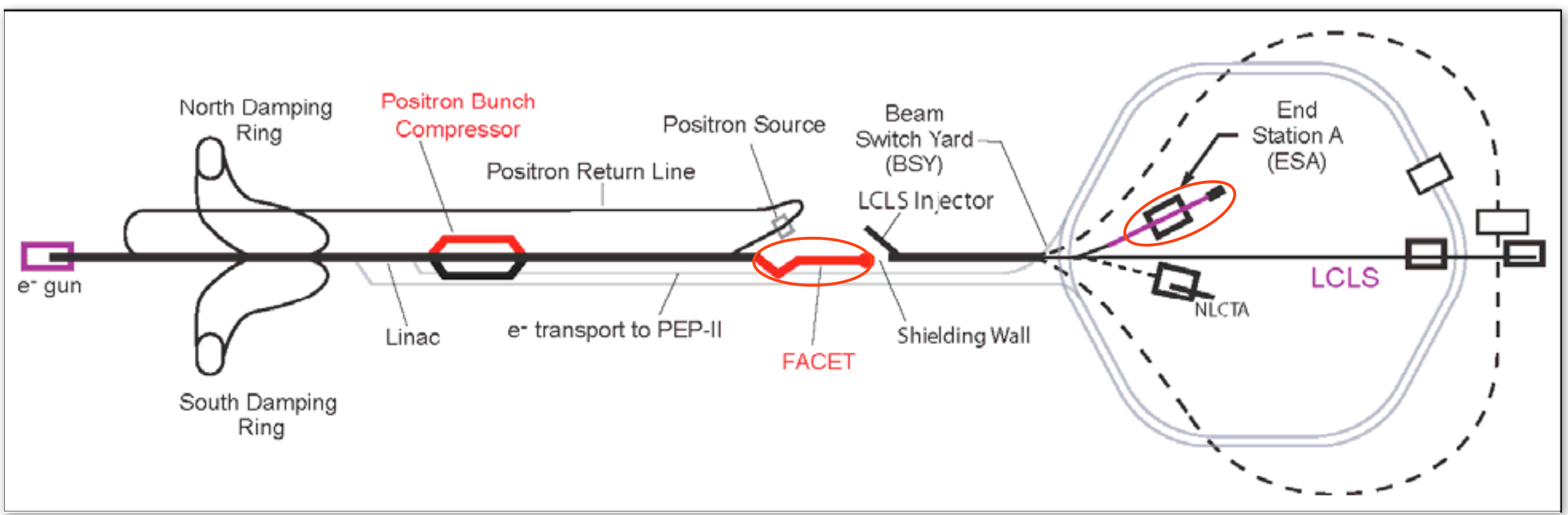
Si (111) Potential for T513 Crystal (ρ = 0.15 m)

$$\theta_{crit} = \sqrt{2U_0/E} \approx 80\ \mu r\ @\ 6.3\ \text{GeV}$$



FACET and the End Station A Test Beam (ESTB)

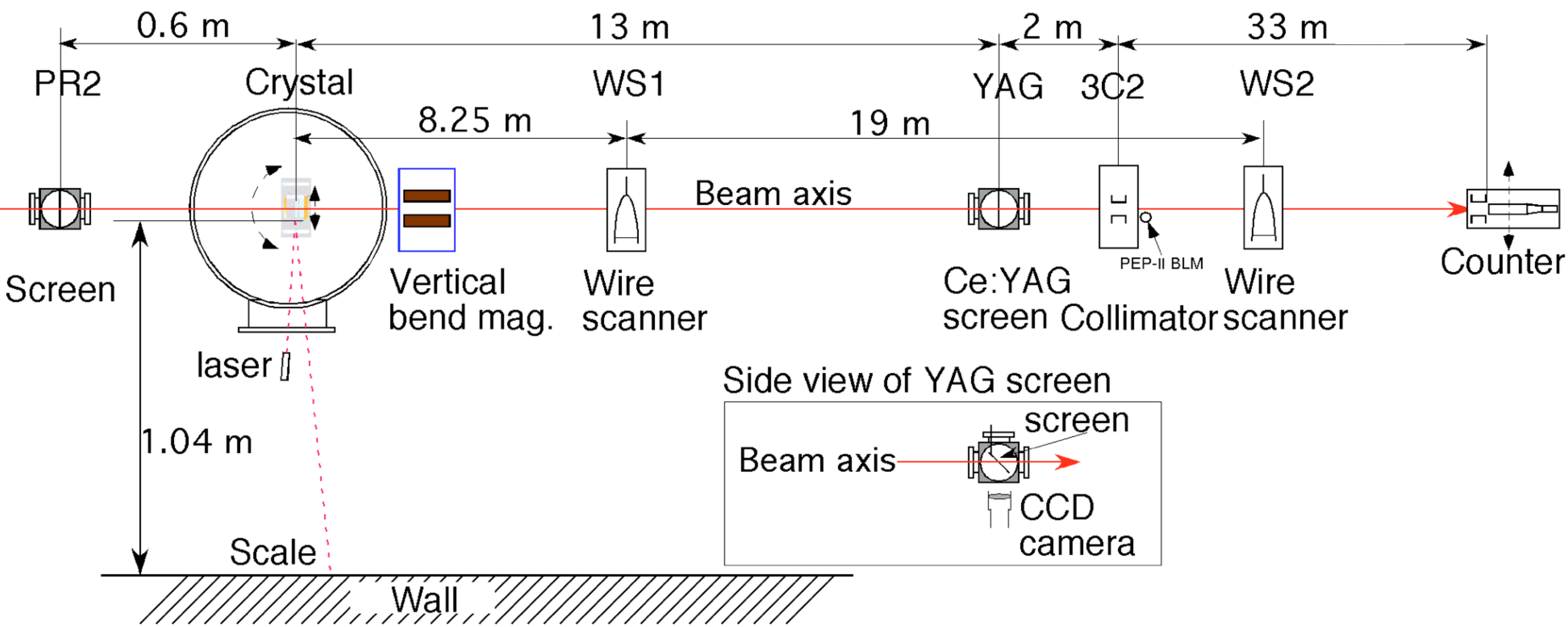
- ESTB: up to 15 GeV e^-, 5 Hz, ≤ 200 pC/pulse
  - "pulse stealing" from LCLS
- FACET: 20 GeV e^+ or e^-, 2 nC/pulse, 10 Hz, "20^3 μm^3"
- control of optics, momentum spread
  - both can provide relatively parallel beam (<10 μrad)
  - FACET has a e^- spectrometer downstream; ≈ 0.1% resolution



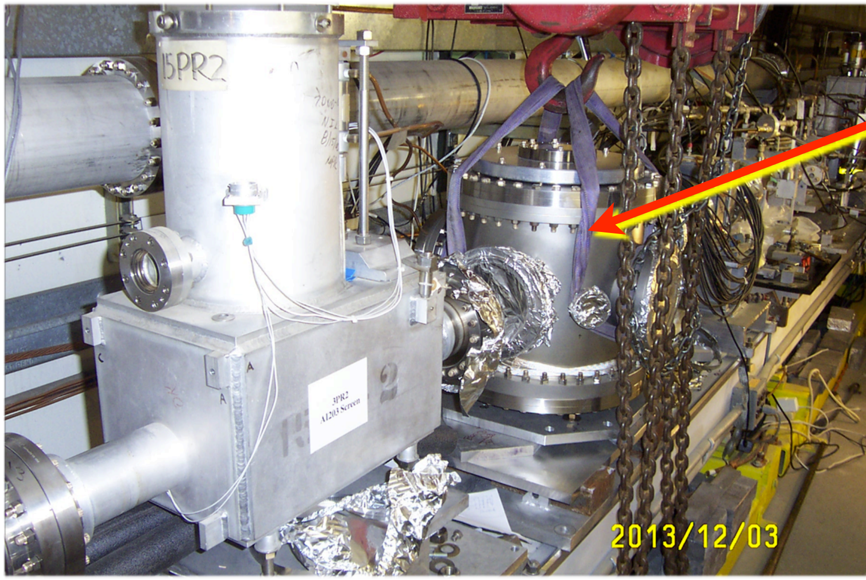
T513/T523 Experiment Layout (ESTB)

Top View, not to scale

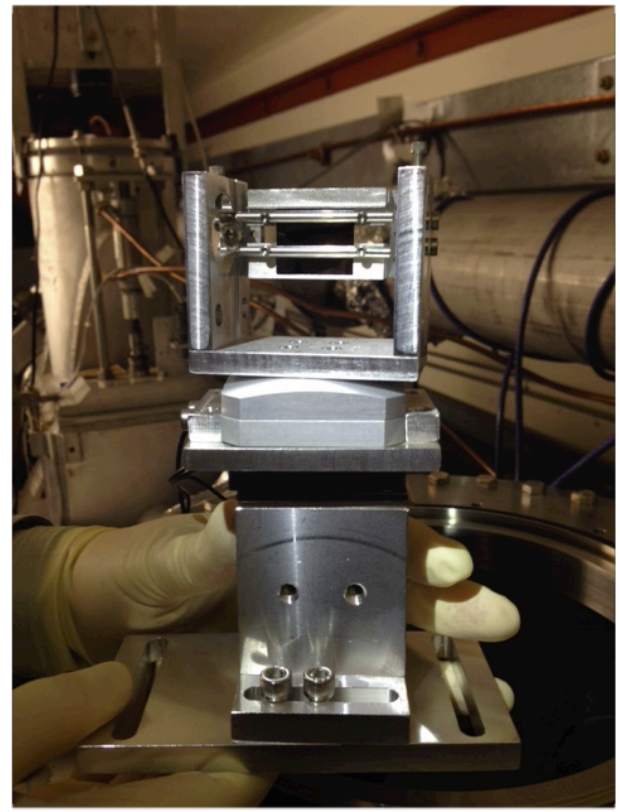
U. Wienands et al., Phys. Rev. Lett. 114, 074801 (2015)



T-513 being installed (by ESTB Group)

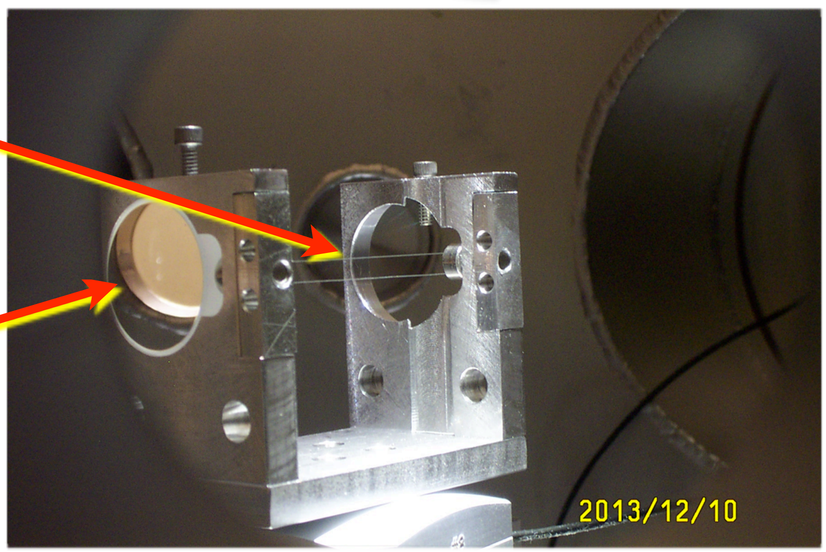


Chamber
("Kraken")

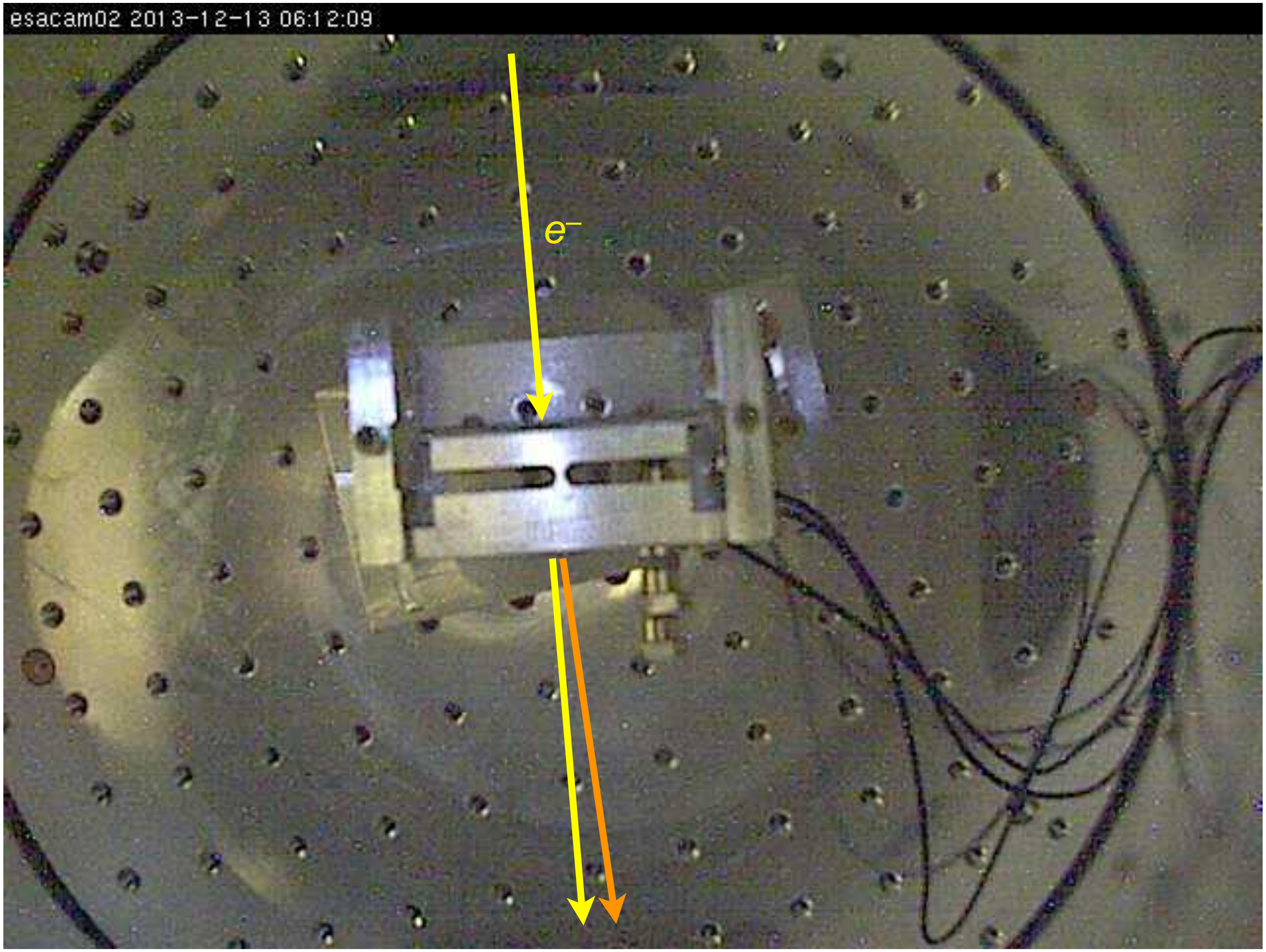


Beam finder wire installed for 1st beam

Mirror for angle readout

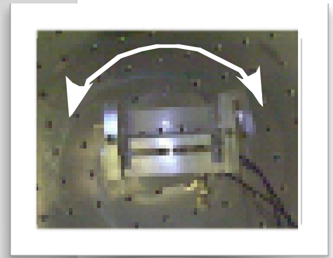


Crystal mounted in “Kraken” Chamber in ESA



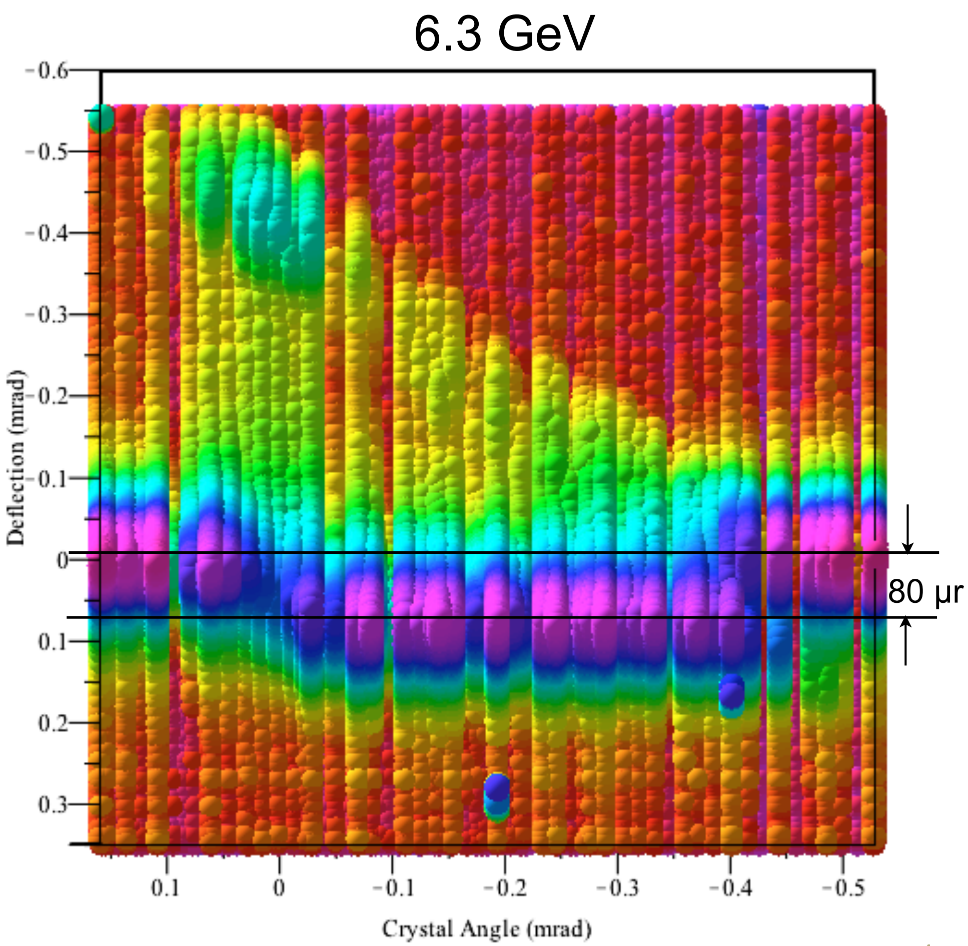
Crystal-Rotation @ 4.2 GeV

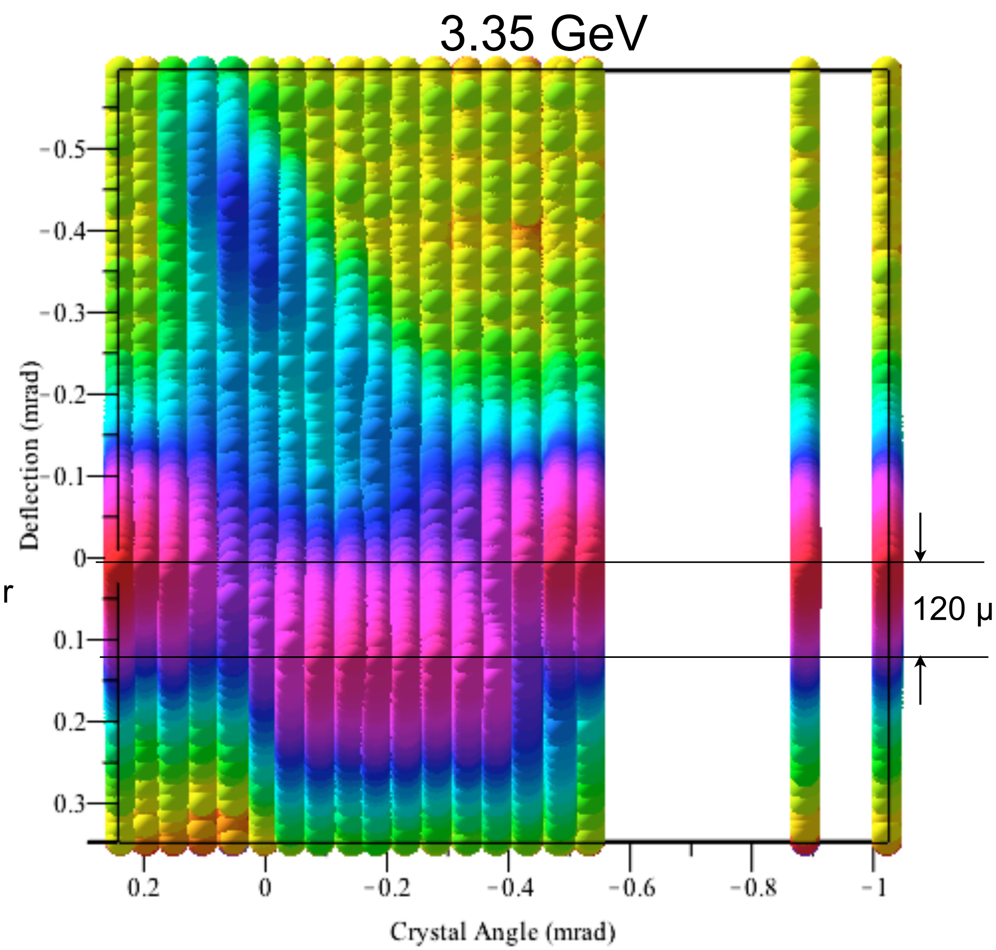
(Movie credit: T. Wistisen)



Triangle Plots

Colors rep. log(intensity).
Crystal angles from fit to laser spot (est'd uncertainty 2…5 μrad)





Fit to Intensity Distribution

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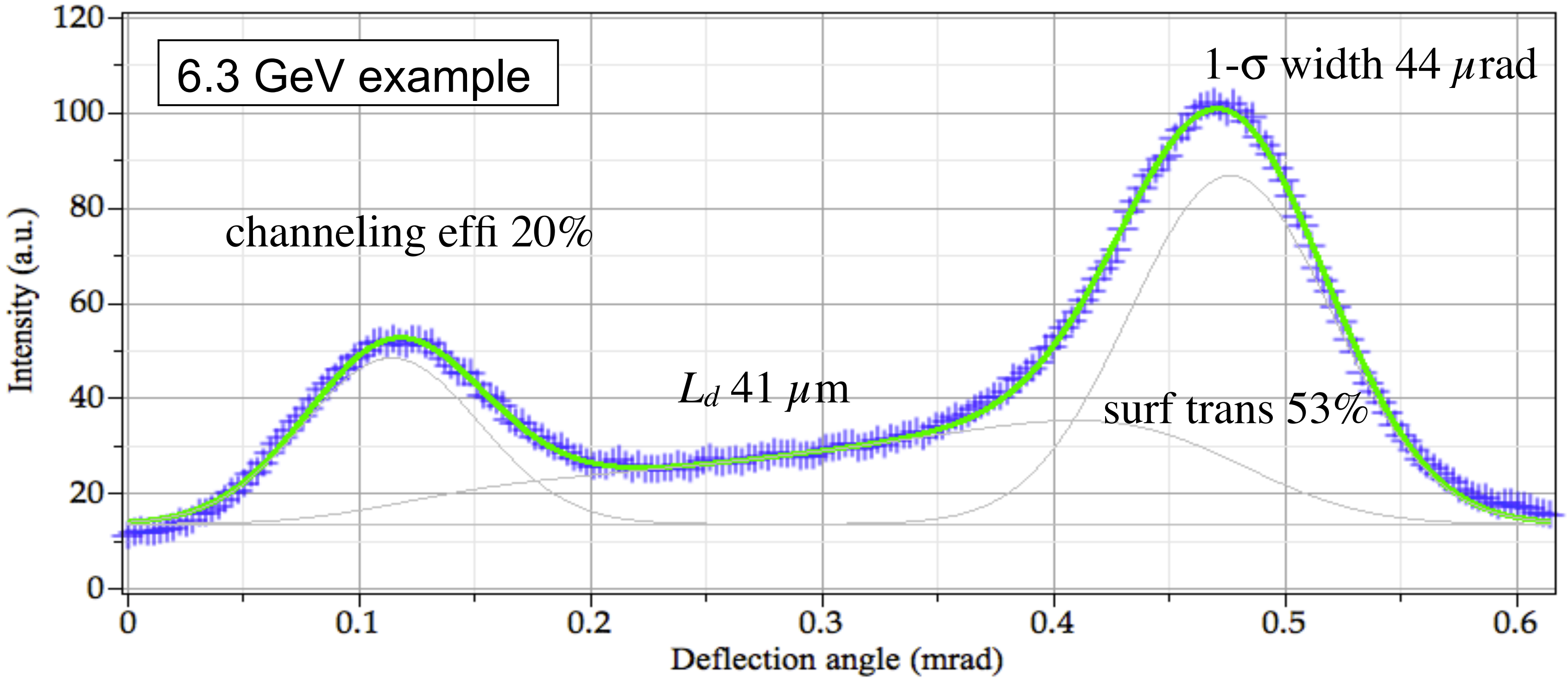
❖unfold 2 peaks + exponential dechanneling tail

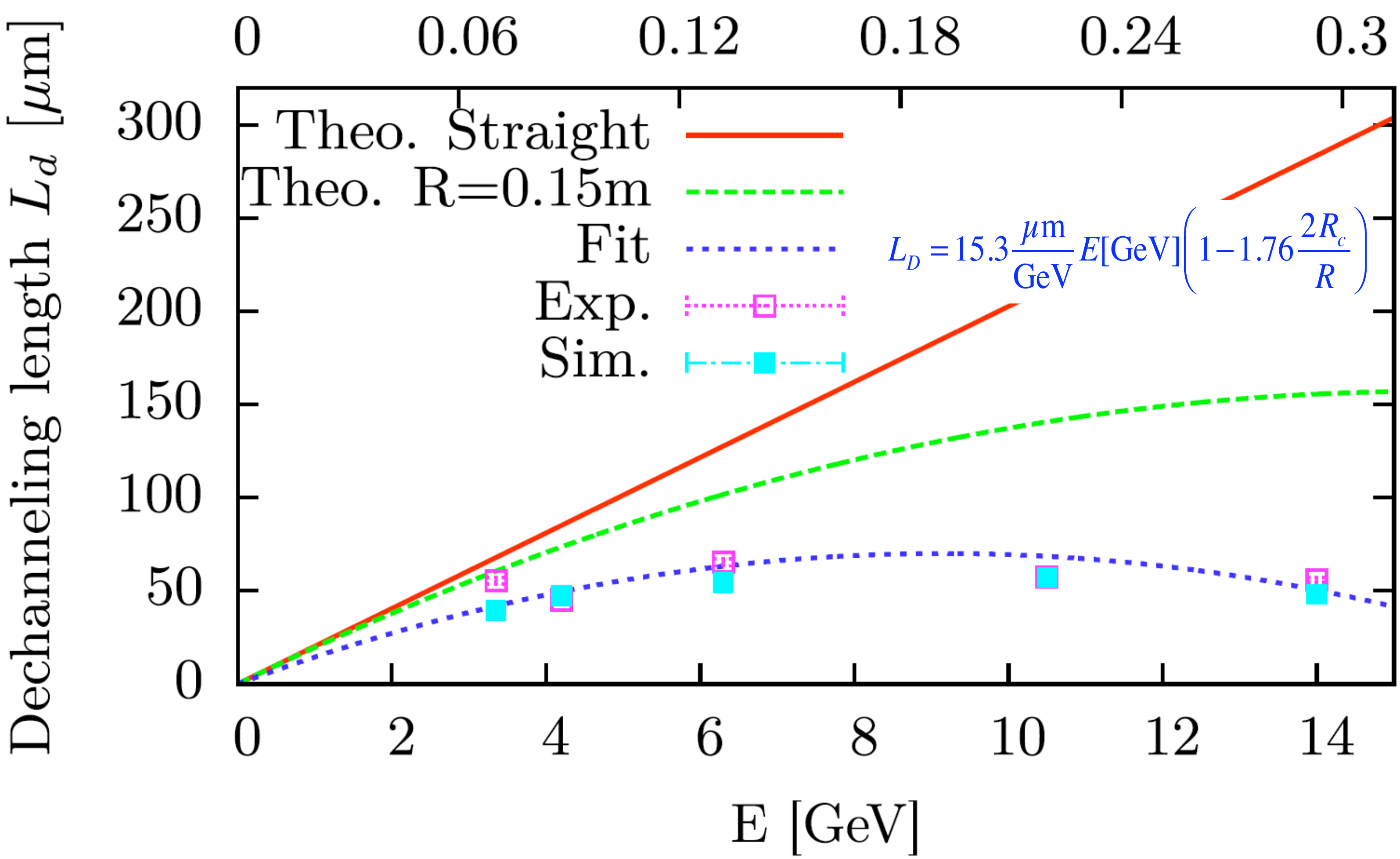


$$\frac{dP}{d\theta}(\theta) = \frac{1-P_1}{2\theta_d} e^{\frac{\sigma_2^2}{2\theta_d^2}+\frac{\mu_1}{\theta_d}-\frac{\theta}{\theta_d}} \left(\mathrm{erf}\left(\frac{\mu_2-\Delta\theta}{\sqrt{2}\sigma_2}\right) - \mathrm{erf}\left(\frac{\mu_1-\Delta\theta}{\sqrt{2}\sigma_2}\right)\right)$$

Channeling efficiency := (channeling peak)/(all)
Surface transmission := (channeling + tail)/(all)
Dechanneling Length := xi/(defl. angle) * (crystal length)

Dechanneling Length of e^-

T.N. Wistisen et al., Phys. Rev. ST-AB 19, 071001 (2016)



Volume Reflection Angle

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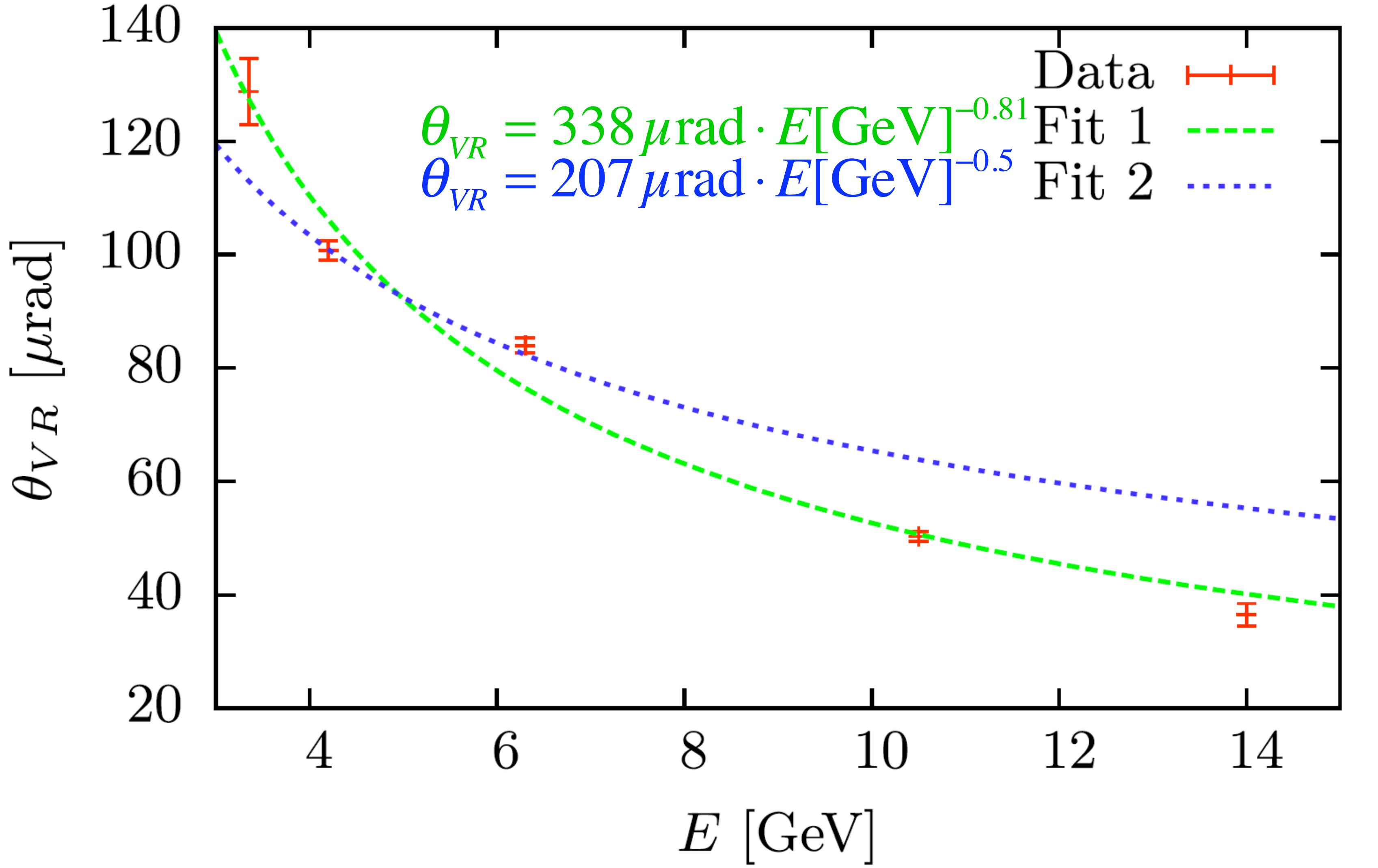
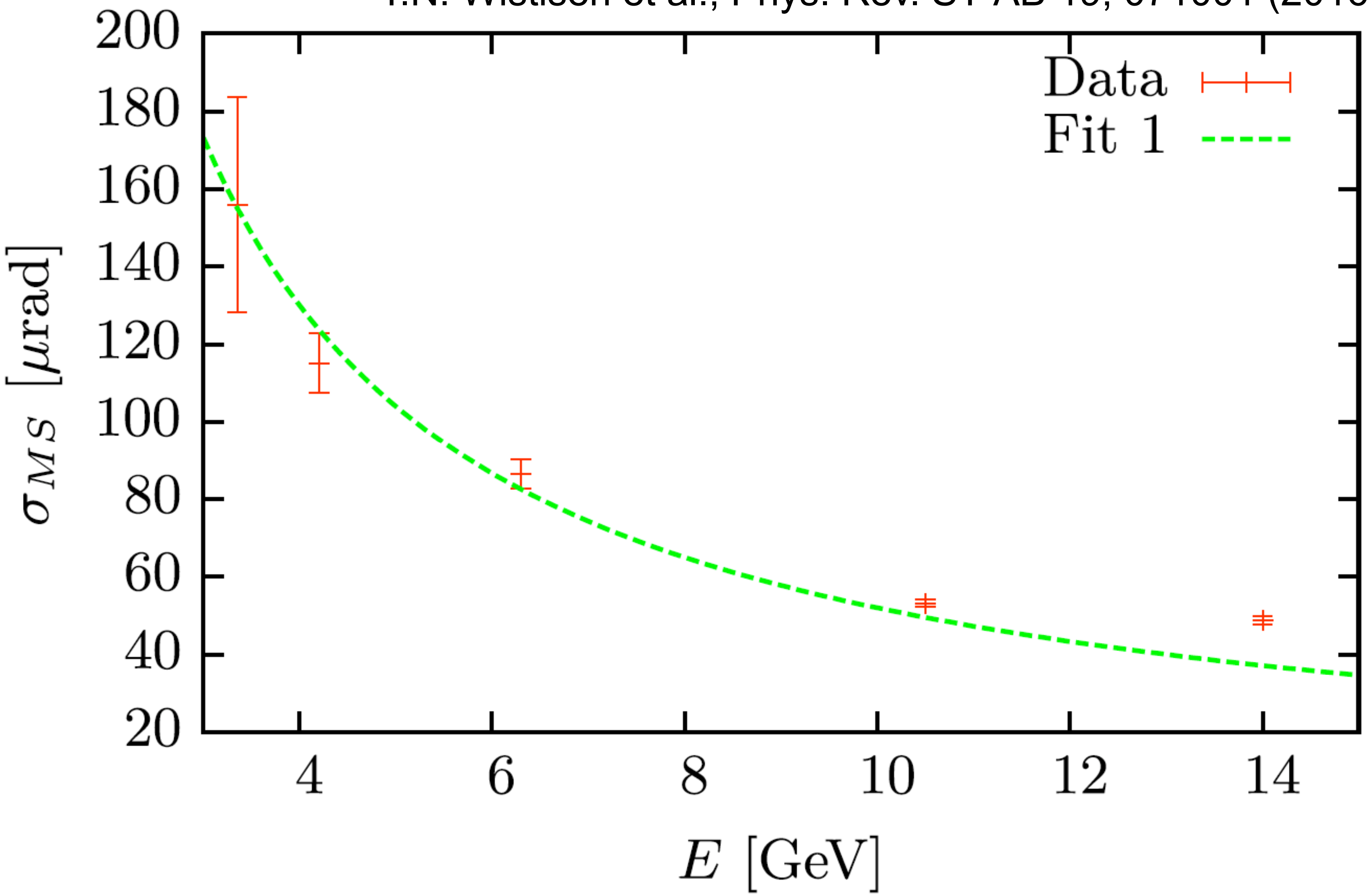
T.N. Wistisen et al., Phys. Rev. ST-AB 19, 071001 (2016)



Scattering in "Free" Direction

T.N. Wistisen et al., Phys. Rev. ST-AB 19, 071001 (2016)

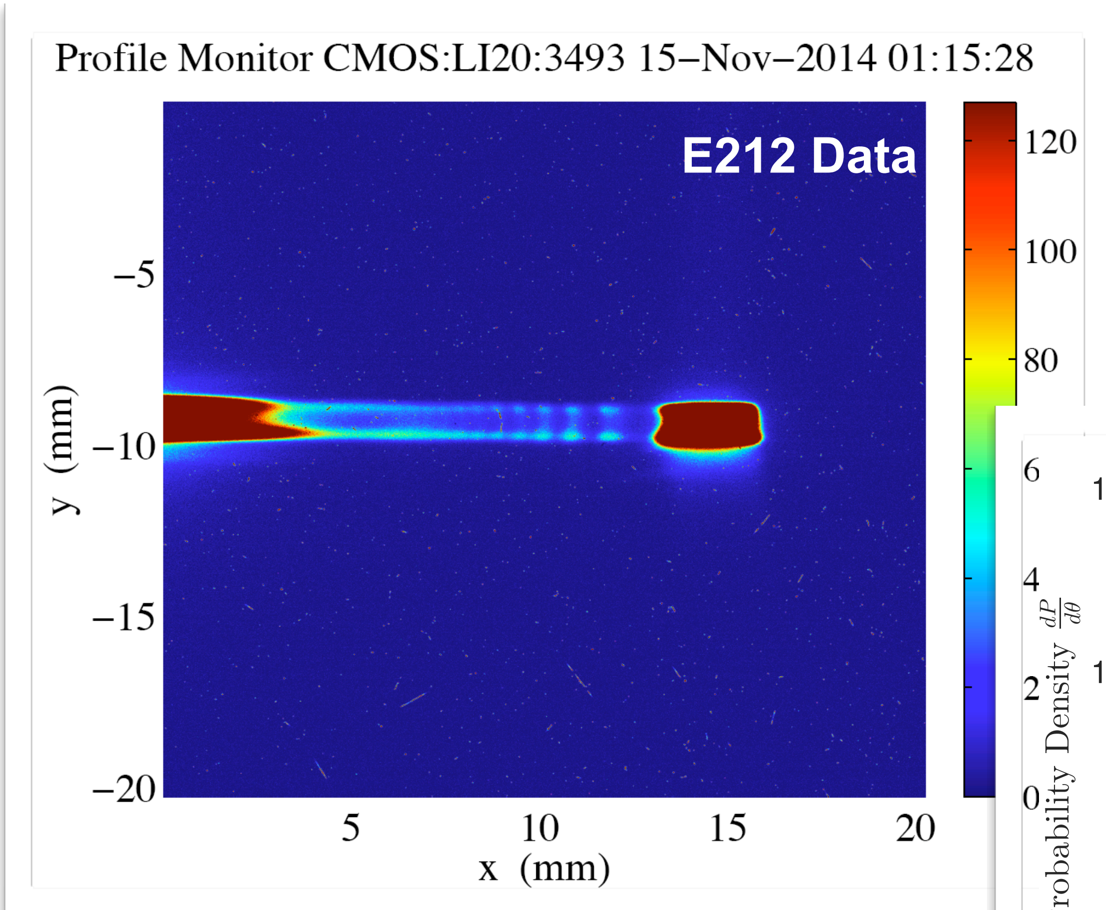


Summary of T513 Results

- Channeling efficiency ≈ 18…24 %, VR up to 95%
- Dechanneling length ≈ 40…60 μm
  - seem to be independent of the beam energy
- Surface transmission 57% (6.3 GeV)…65% (3.35 GeV)
  - calc: 57% @ 6.3 GeV (Wistisen)
- Scattering seems enhanced in the vertical plane for channeled particles
  - by roughly a factor 2 (X0 –> X0/4)

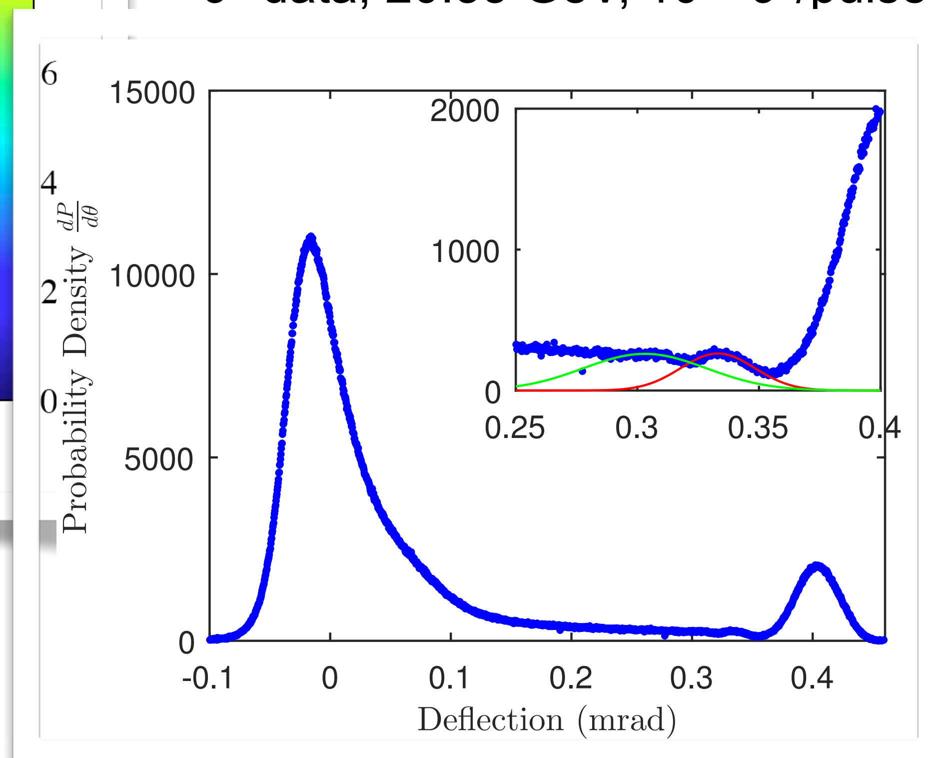
E212: First Channeling Data of e^+ in Bent Crystal

- 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"

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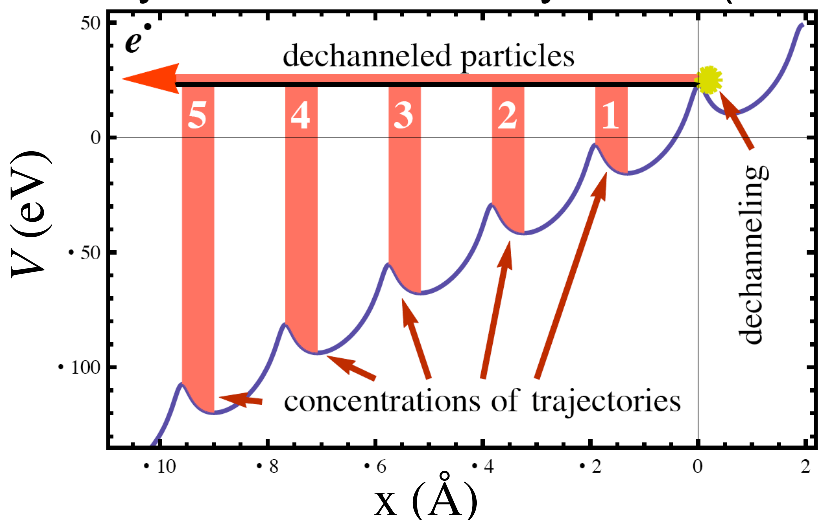
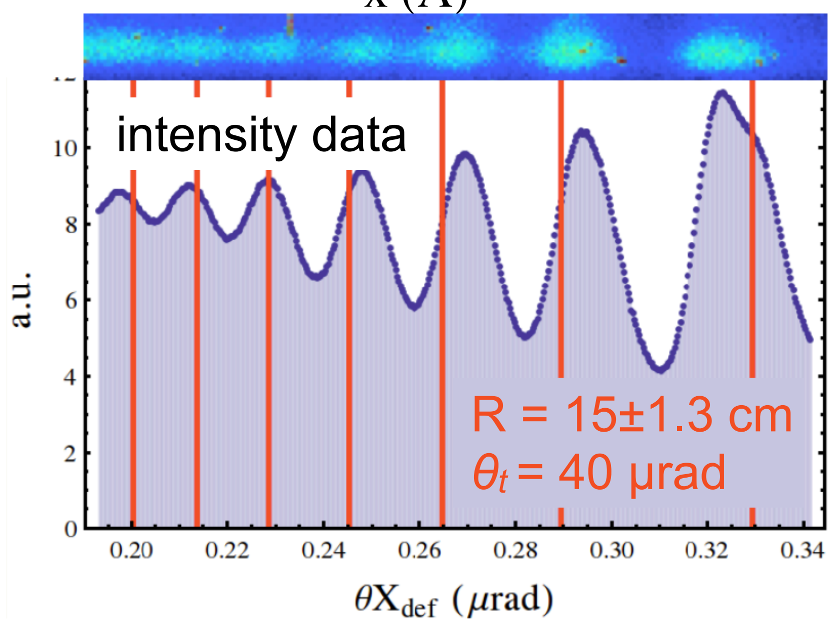
A. Sytov et al., Eur. Phys. J. C (2016) 76: 77

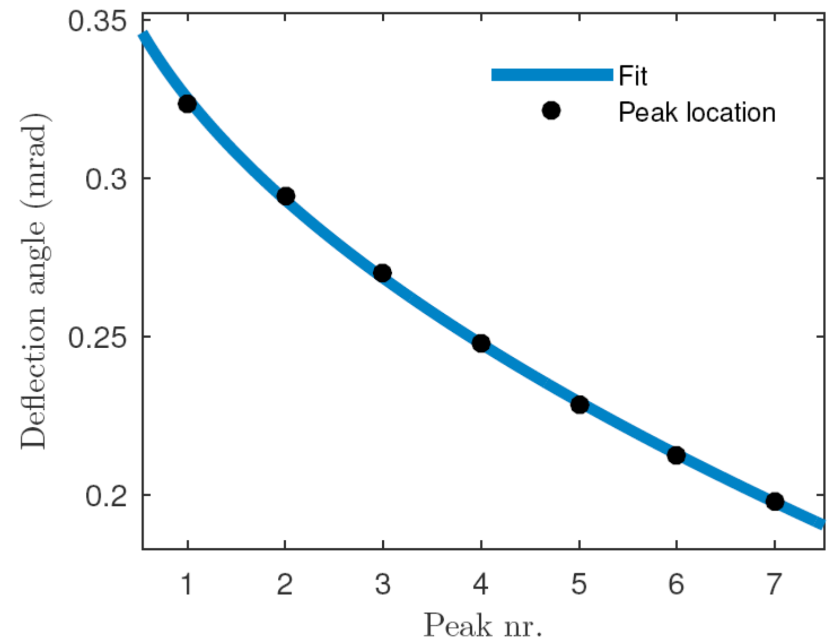




R. Mikkelsen et al., in prep.

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

$\theta_b = 402 \pm 9\ \mu$rad, $R = 0.15$ m,
$d_s = 3.14$Å (known), $d_0 = 4\ d_s$

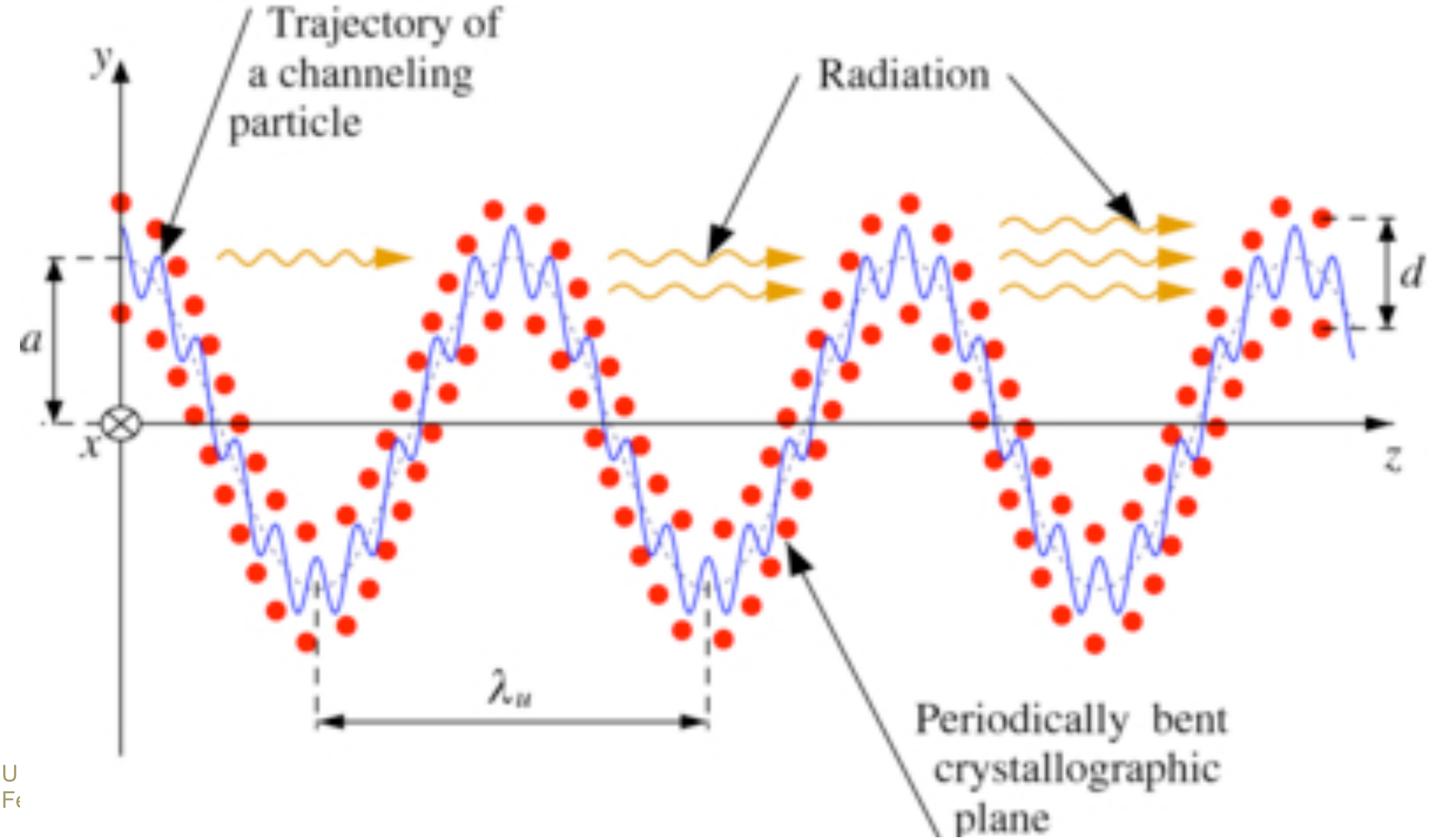


Radiation (apart from brems & CBR)

- Channeling radiation
  - smooth bend… synchrotron-like
  - betatron oscillations… undulator-like; but only for e^+
- VR radiation
  - synchrotron-like, harder than channeling radiation
- Undulator
  - E212 @ FACET
    - “Kostyuk” undulator
  - T523 @ ESTB
    - “Volume-reflecting” undulator
- Parametric X-rays (not treated here)

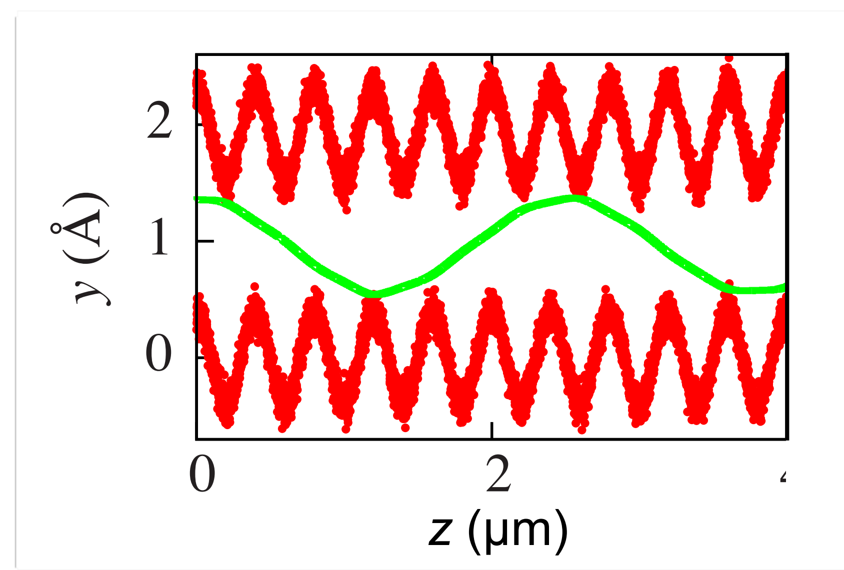
Crystal Undulator (Solov'yov, Korol, Greiner et al.)

Fast betatron oscillation, "slow" crystal undulations.
Expected to work with e^+, but e^- don't channel well enough.



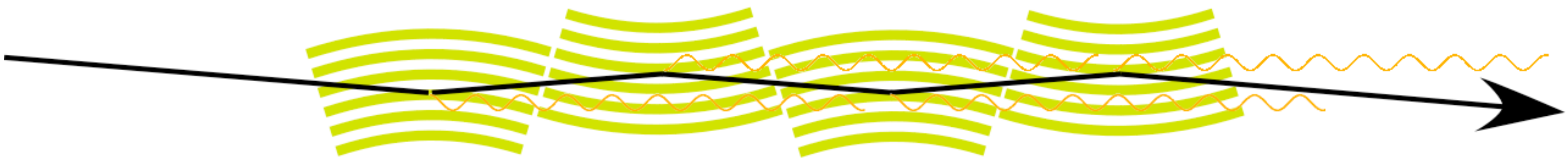
Kostyuk Undulator

- "Slow" betatron oscillations, fast undulations
  - Undulator period < betatron period
  - supposed to work with electrons as well.
- E212 undulator: strained lattice Si (111) crystal
  - variable doping with Ge creates undulations
  - 4 μm long, 10 periods
  - some signal at 850 MeV (MAMI); too short for 20 GeV (FACET)
  - longer version (30 μm) now in hand
    - test likely in August

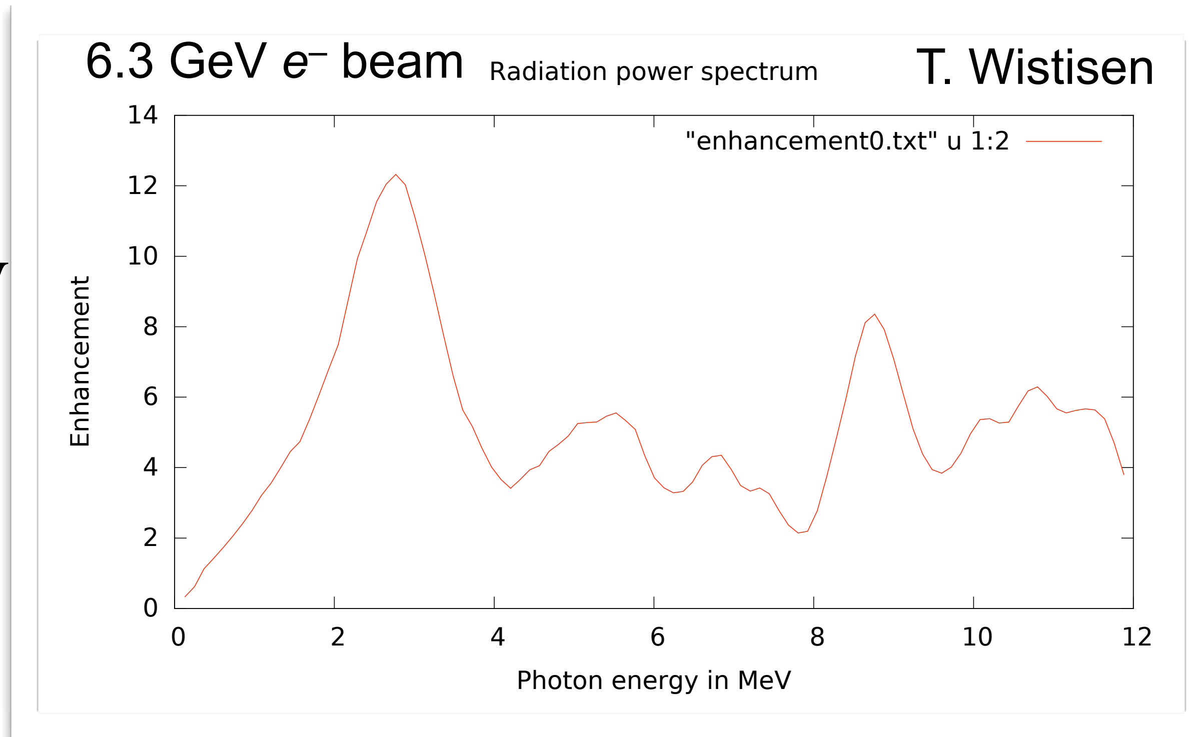


VR Undulator

- Stack of bent crystals; T513-crystal-like



- Acceptance: θ_b–θ_{crit}
  - ≈ 300 μrad for T513 xtal
- MS: 30 μrad @ 10 GeV
  - 10 periods: 135 μrad, < 300 μrad
- A 10 period undulator could work!



10-Period Undulator Estimate

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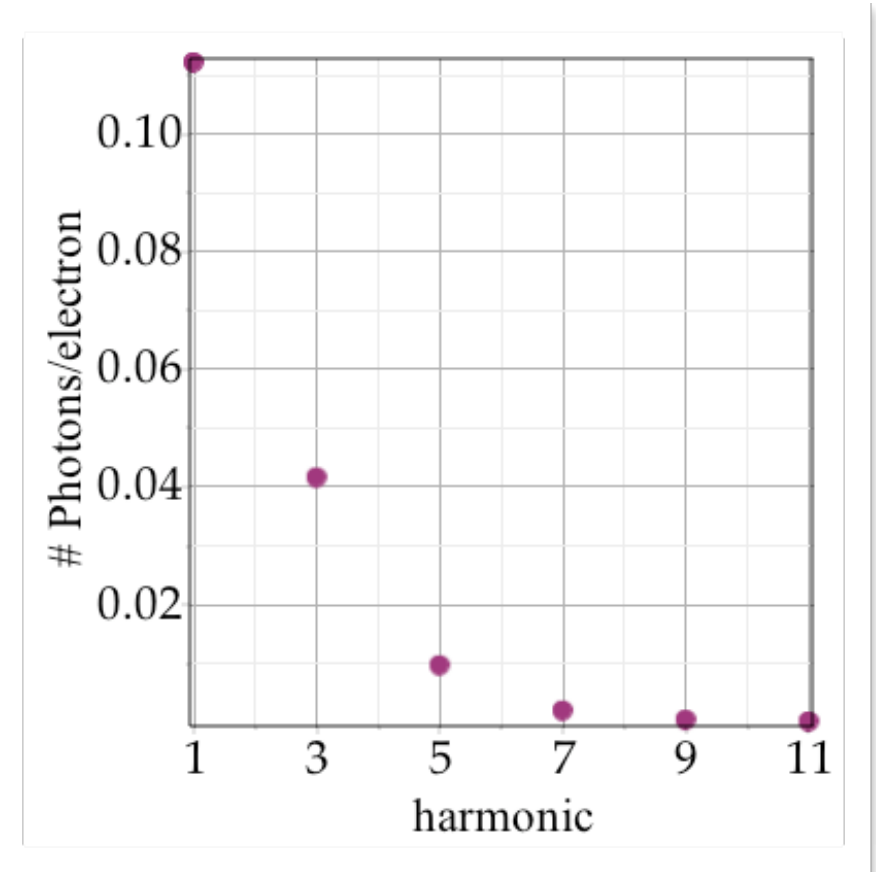
- Assuming 60-μm crystals like ours; 20 GeV (FACET):
  - K≈0.9 (scales w/√γ)
  - $N_{photons}$: 2×10^9 in 1st harmonic (2×10^{10} e^- /pulse)
  - 0.10 photons/e^- in 1st harmonic
  - $\sigma E \approx 0.13$ MeV



(≈ 2.7 MeV/harmonic)

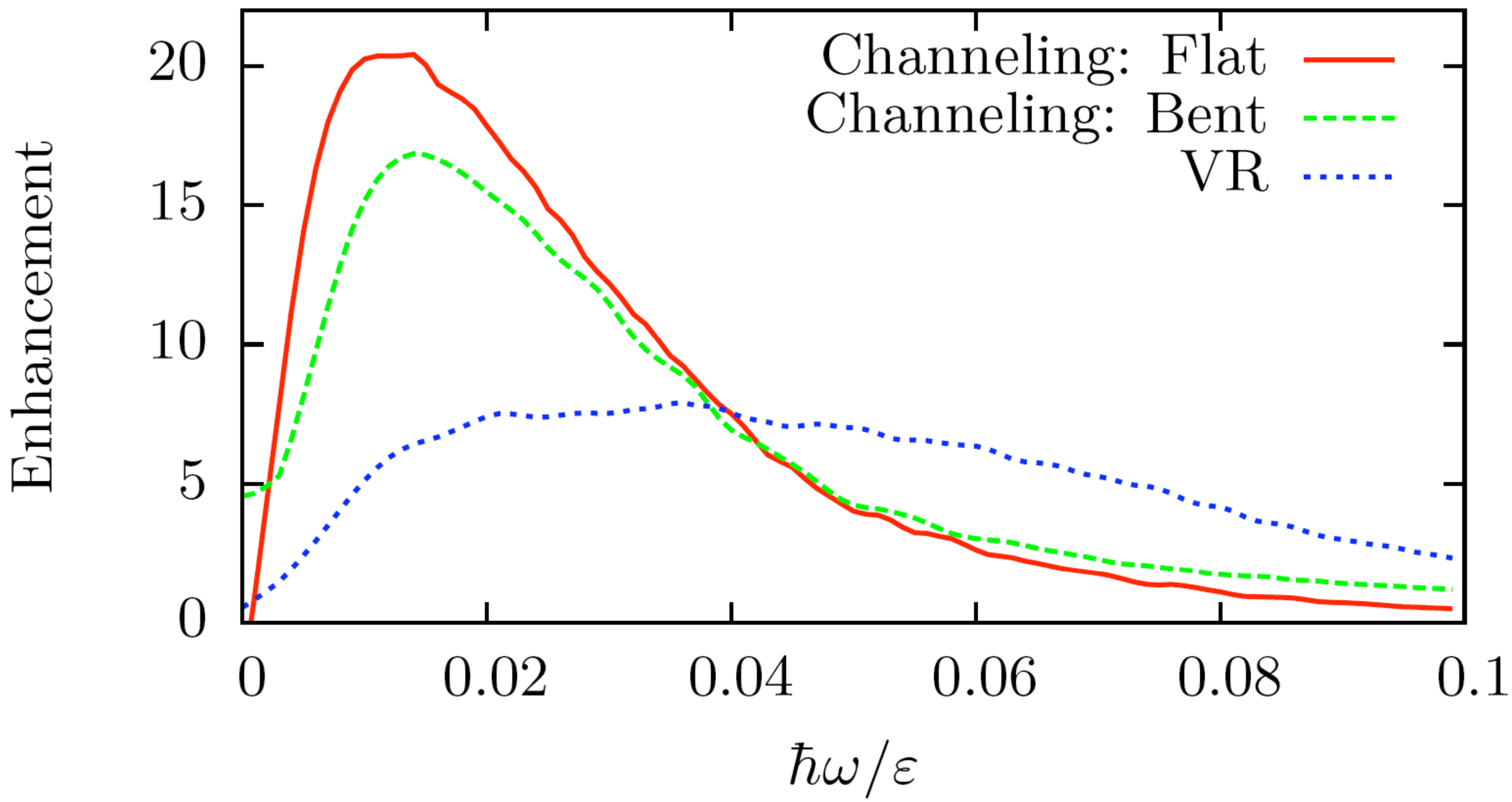
- A typical Compton source may produce 0.03 photons/e^-
  - crystal competitive in intensity
  - needs development to reach brightness.

Radiation Spectrum (10 GeV e^-)

photons: $$\frac{dN}{d\varphi}=\frac{4\alpha}{9}\gamma\frac{\Delta\omega}{\omega}S\left(\frac{\omega}{\omega_c}\right)N_{e,pulse}$$ $\approx 3\text{x}10^7$ for $1\text{x}10^9$ e^- $(\Delta\omega=\omega)$

single crystal

T. Wistisen



Gamma-Ray Experiment (T523)

- Use sweeper dipole to dump electrons on 3C2 collimator
- Scintillating-Fiber calorimeter for gamma-spectroscopy
  - necessitates single-photon counting to get spectrum
  - Collimator in *X* to define angle of gammas

- Difficulties:
  - single-particle beam => “flying blind”
    - setup with full intensity
  - electrons dumped close to beam line
    - signal-to-noise ratio a concern

High-Intensity spectra

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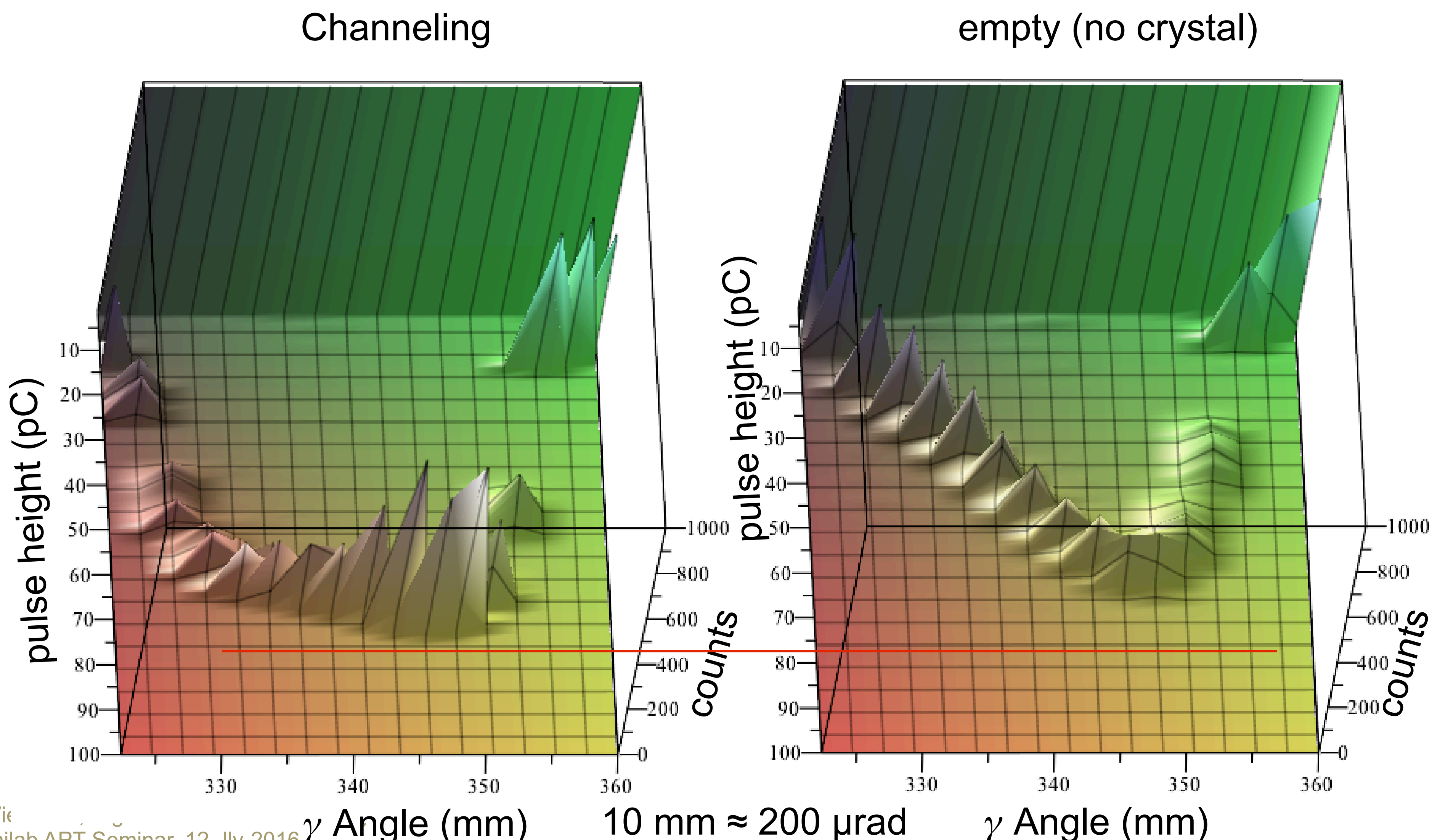
energy-weighted pulse height spectra of $\sum E(\gamma_n)$



Single-Photon spectra (bkg subtracted)

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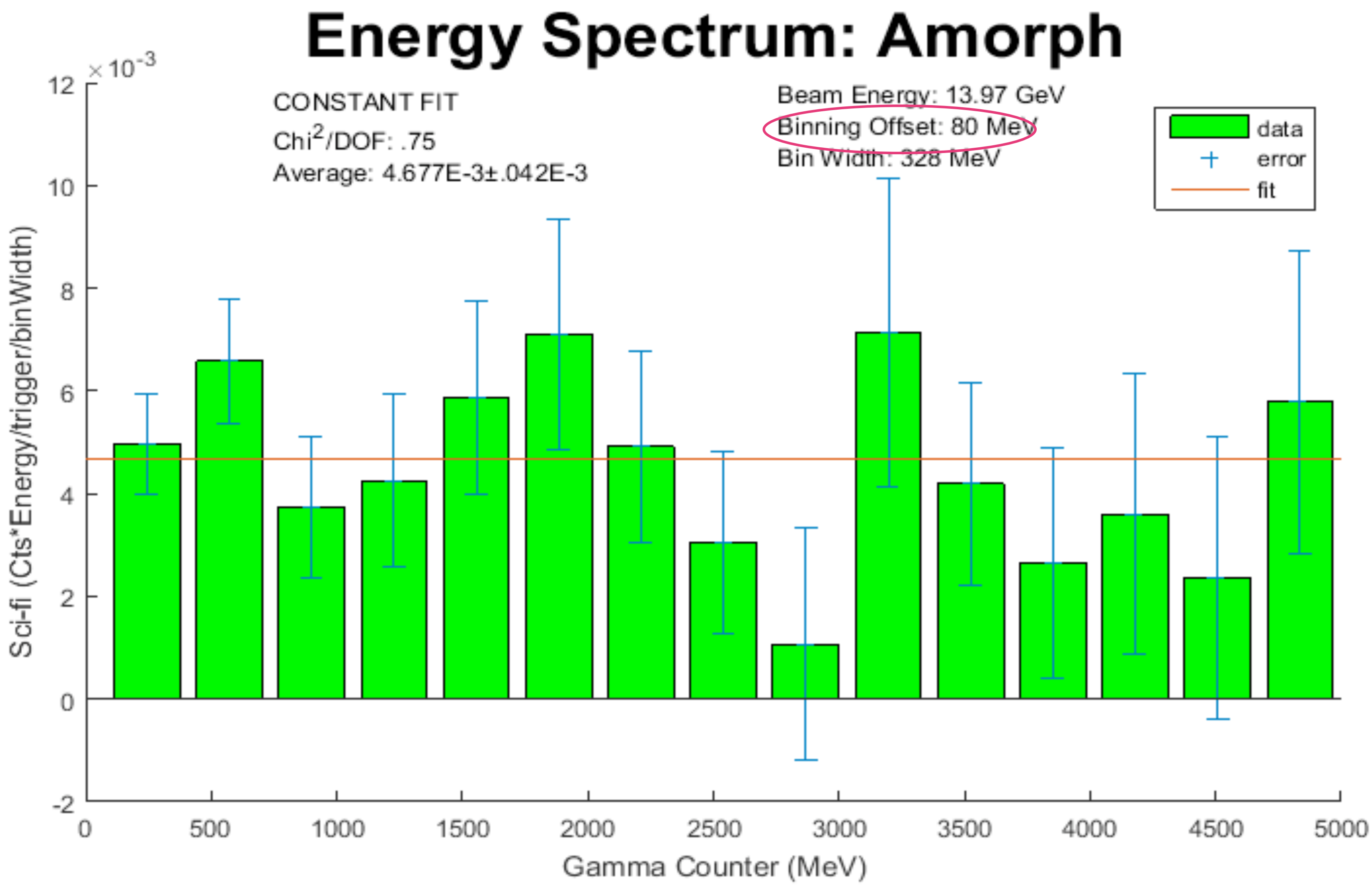
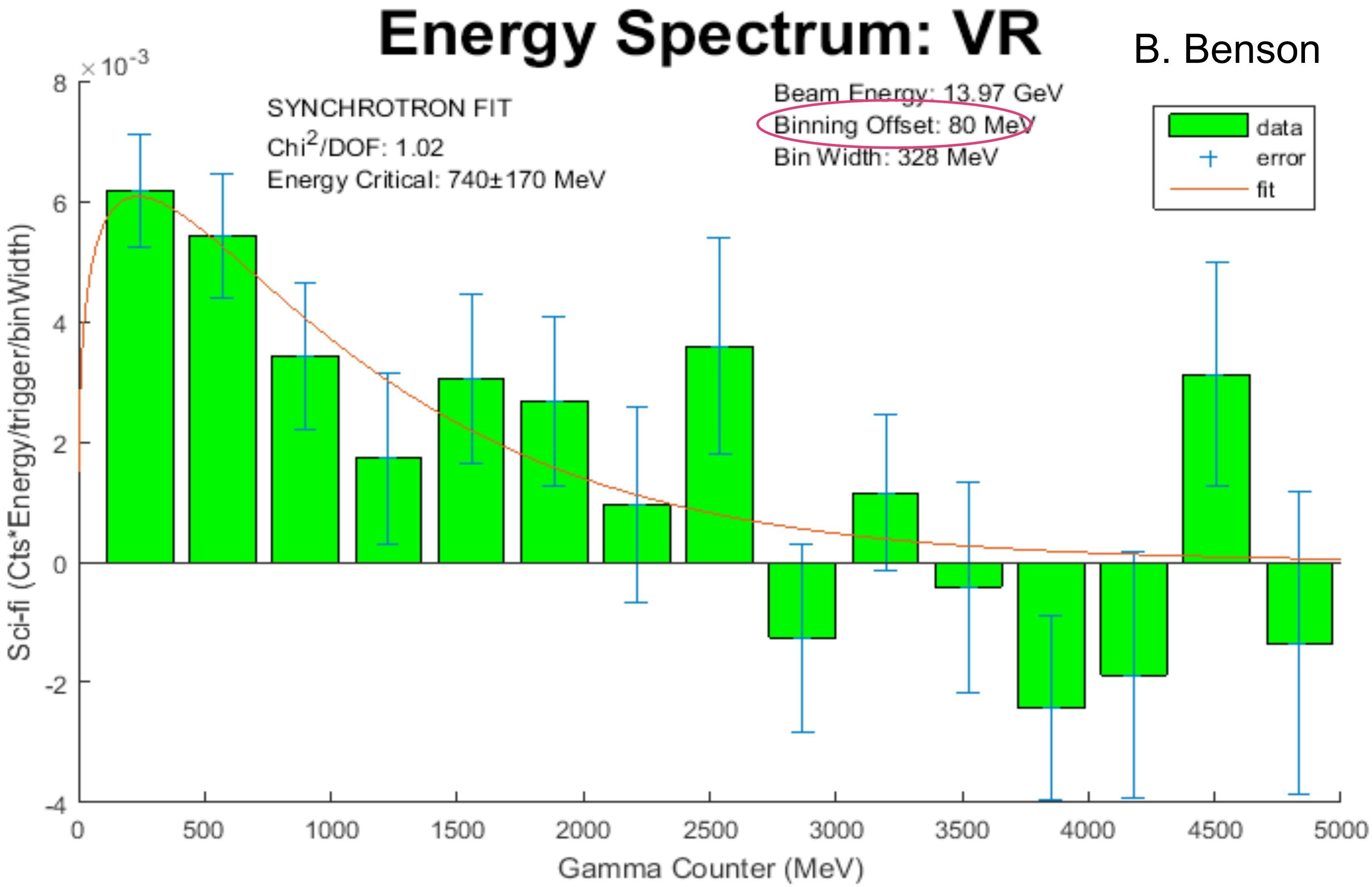


Single-Photon spectra (bkg subtracted)

Total tally above 80 MeV: ≈ 0.02 photons/electron



Comment to (single-photon) Spectra

- The amorphous spectrum is flat as expected
- The VR spectrum is consistent with synch. radiation
  - E_{crit} ≈ 740 MeV => ϱ ≈ 8 mm, localization a few μm.
  - Not clear whether there is an *enhancement* over Bethe-Heitler.
- The channeling spectrum is too weak to make a statement
  - probable cause is unfortunate choice of angle (cf. high-intensity spectrum)
- Signal-to-noise is about 1:1

Next Steps

- Improve gamma-radiation data quality
  - identify and mitigate background source(s)
    - Geant4 simulation of beam line & collimation (Bagli)
    - better shielding of collimator
  - Increase event rate (factor ≈ 3 before pile-ups become issue)
  - lower detection threshold (need factor > 10).
  - Try new Aarhus undulator crystal
- Build a Compton spectrometer
  - allows much higher data rate, full intensity beam.
  - Trade efficiency for resolution
  - limits gamma energy range from 0.1 to 10 MeV.
  - Use LANL spectrometer??

Summary

- Deflection data provide a wealth of information in an unexplored energy region of channeling
  - constancy of dechanneling length not understood.
- "Quasi-channeling" wiggles indicate understanding of details of the beam dynamics within crystals.
- Radiation experiment difficult (as expected)
  - clear evidence for radiation, excess over Bethe-Heitler not proven
  - VR spectrum consistent with synchrotron radiation.
  - Hi-intensity spectra show channeling radiation; single photons ?
- To explore VR undulator, we need
  - increase data sample by about a factor 10
  - increase signal-to-noise ratio by a few
  - lower energy threshold by at least a factor 10