e^+ and e^- Beam Interactions with Crystals at SLAC FACET and ESTB

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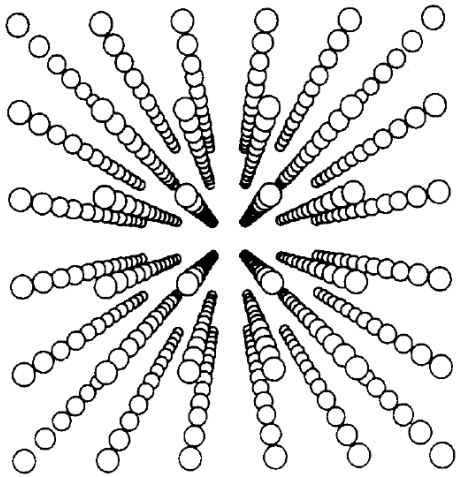
Office of Science

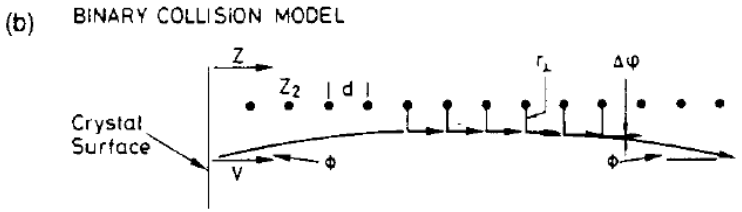
Motivation

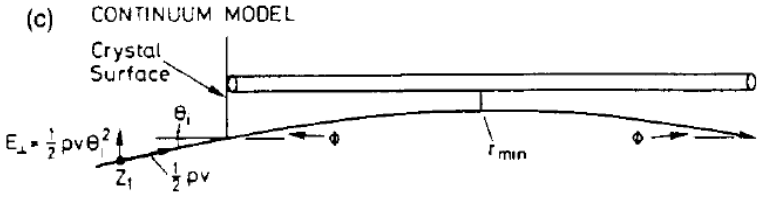
SLAC

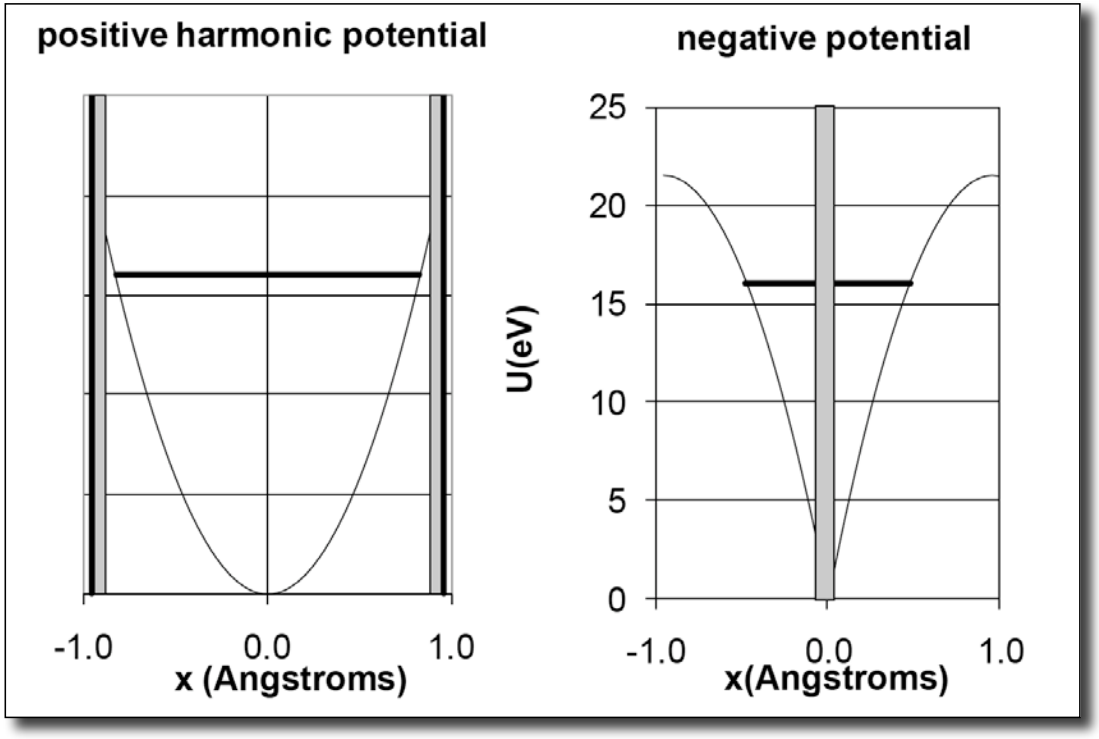
- Bent crystals can deflect high energy beams with small bending radii (O(0.1m))
  - lots of proton data, little data for high-energy e^- or e^+
- **There is interest in crystal collimation for e^+ and e^-**
  - Expected benefits in size and efficiency of collimation
  - Not enough data to actually design such a system
  - Possible application to ILC, LCLS-II
- **There is interest in 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

Channeling Potentials







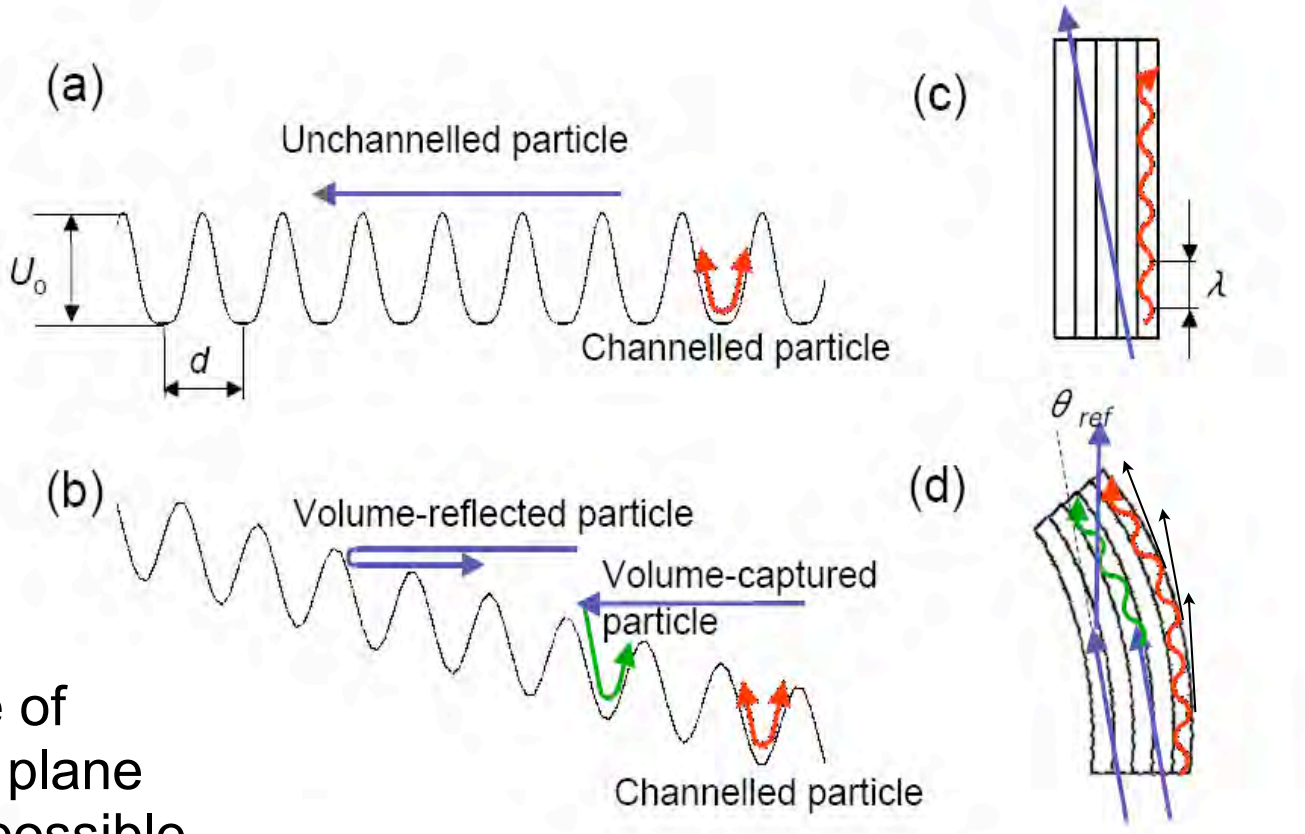


Particle-Crystal Interaction

W. Scandale (adapted)

Possible processes:

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



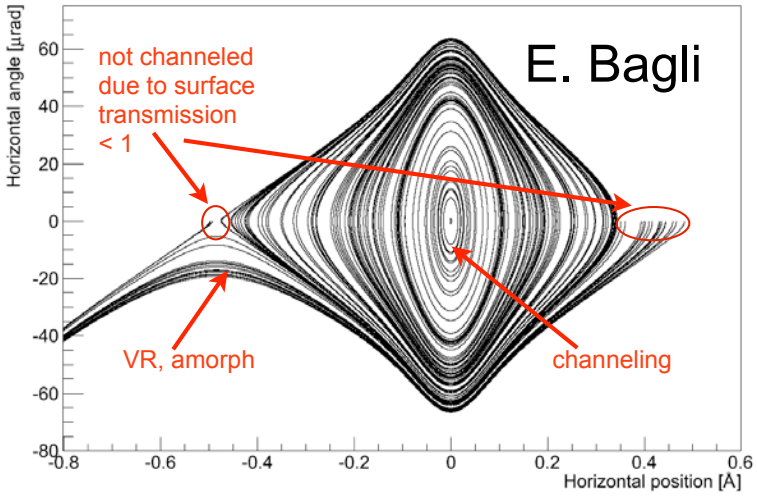
Critical angle: max. angle of incoming particle against plane where channeling is still possible

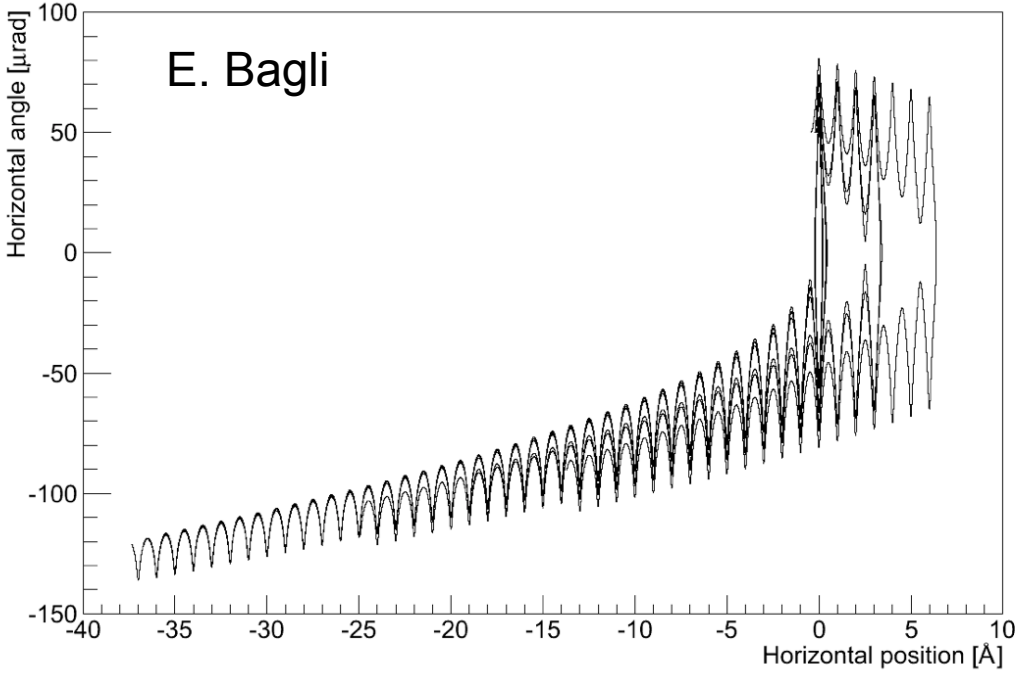
$$\theta_{crit} = \sqrt{2U_0/E}$$

Dechanneling rate ∝ # in channel => ∝ e^{-s/L_d}; L_d is called *dechanneling length*

Volume Reflection

- Deflects p,e^+ by ≈ 1.4…1.8*θ_{crit}, the critical channeling angle
  - independent of crystal length
  - scales with $1/\sqrt{E}$
  - bending angle = VR acceptance in beam divergence angle.
  - Will incur multiple scattering (channeling + particles don't ?)
- e^- undergo VR as well



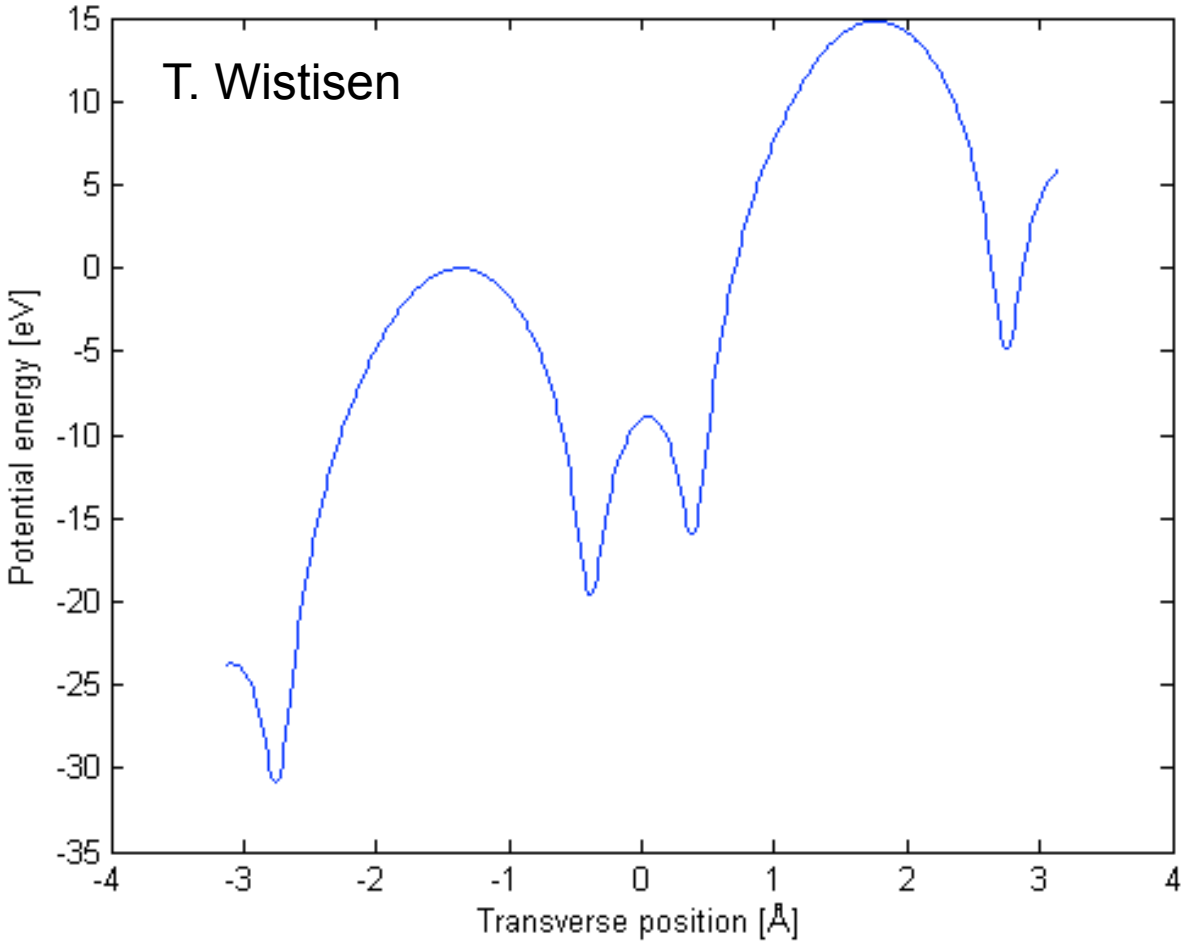


Main crystal features

- **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.**

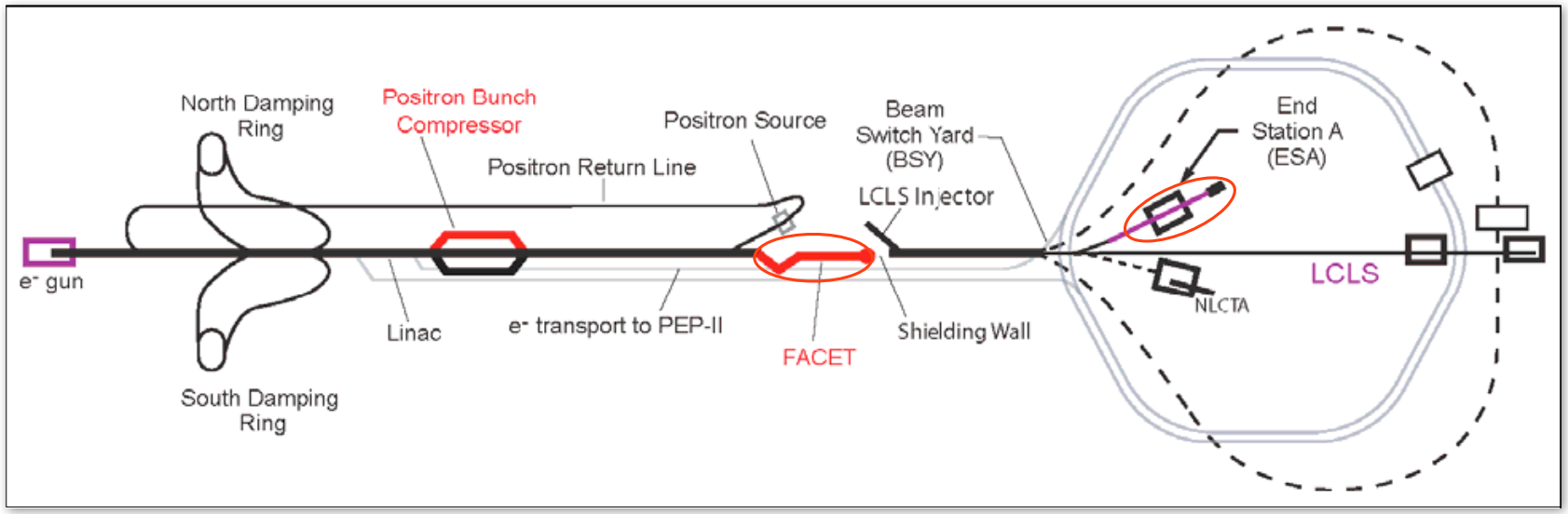
Si (111) Potential for T513 Crystal (ρ = 0.15 m)

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



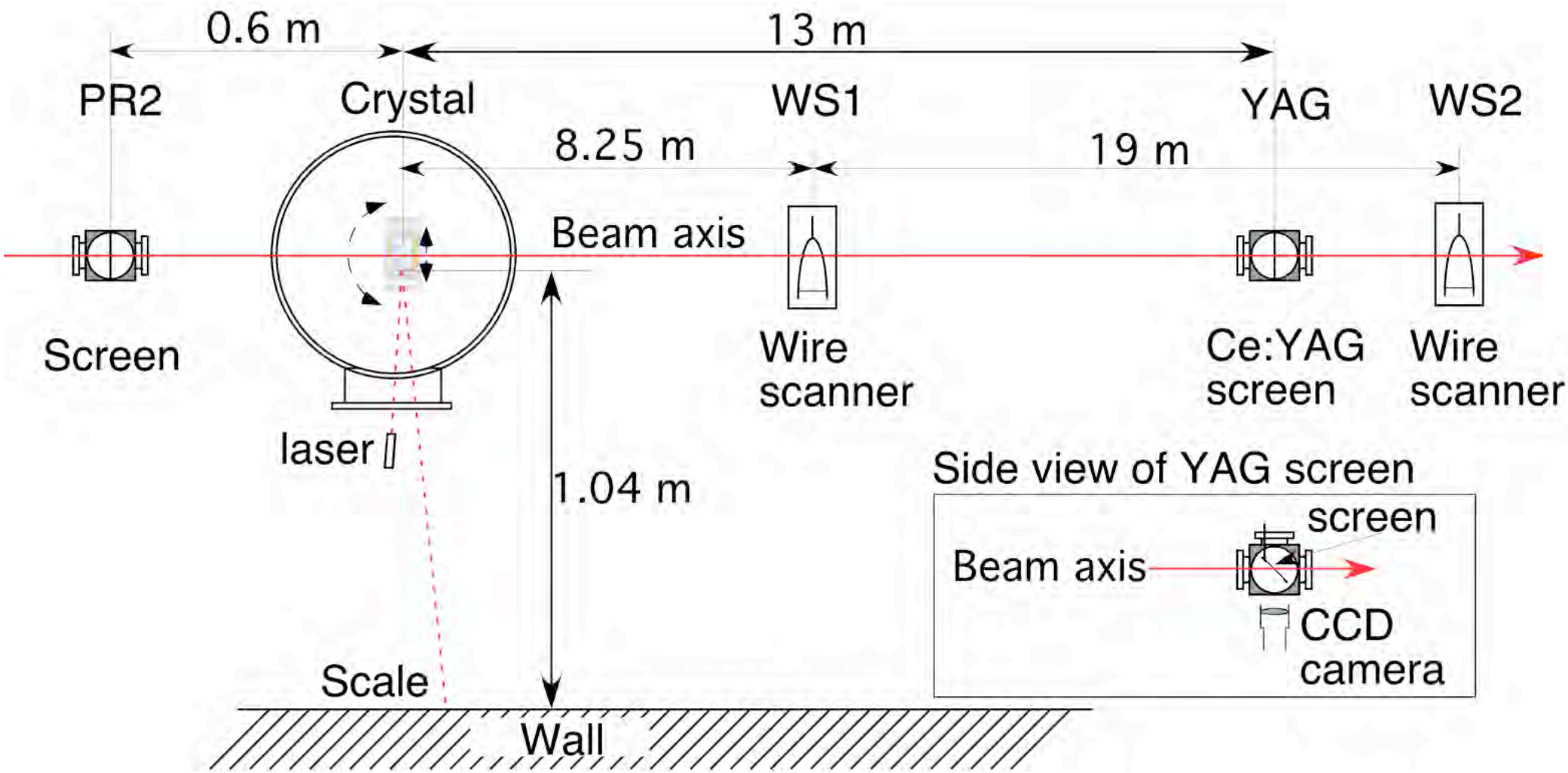
FACET and the End Station A Test Beam (ESTB)

- ESTB: up to 10 (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 spectrometer downstream; ≈ 0.1% resolution

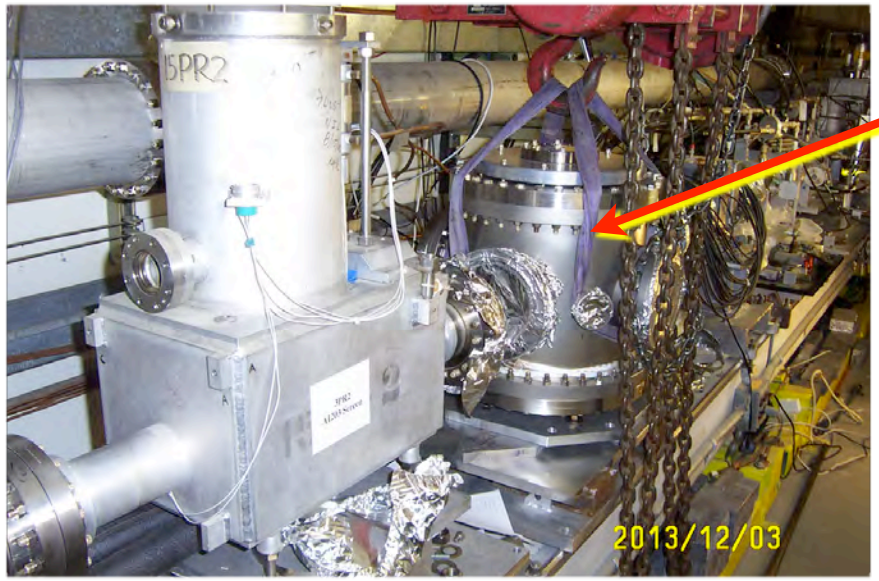


T513 Experiment Layout (ESTB)

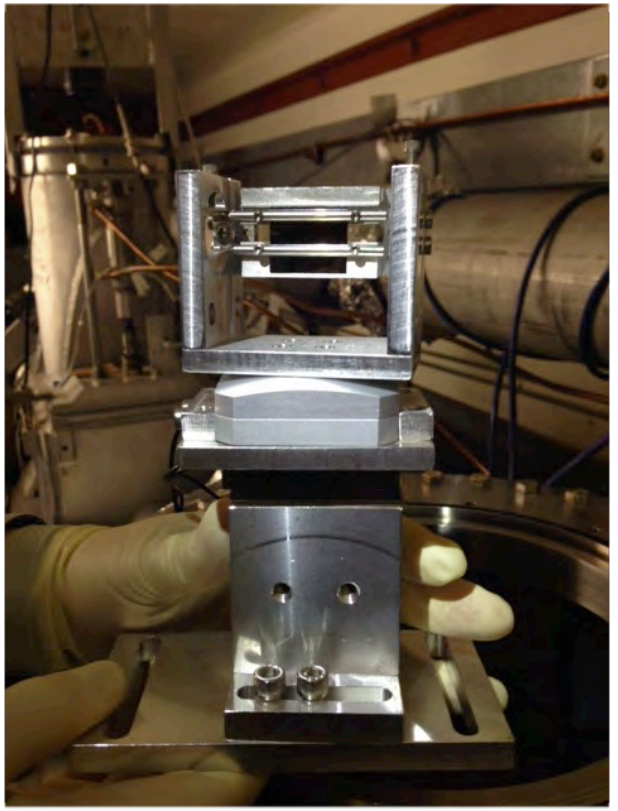
Top View, not to scale



T-513 being installed (by ESTB Group)

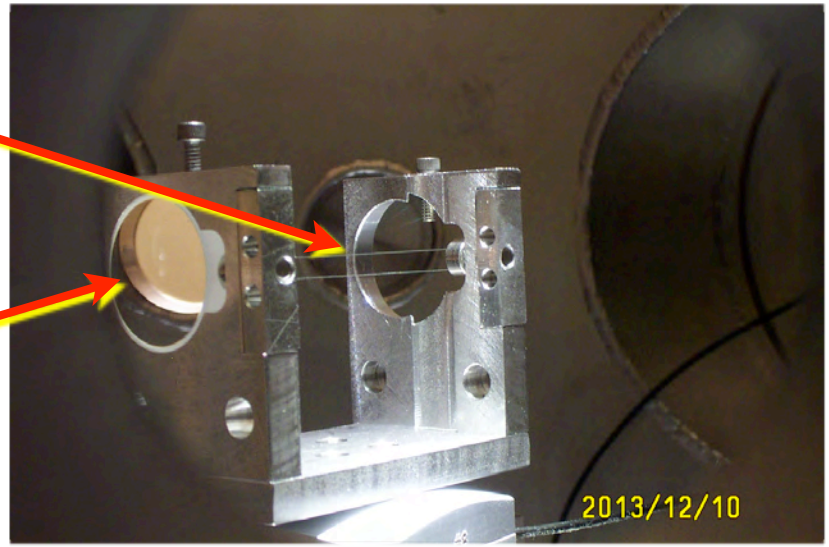


Chamber
("Kraken")

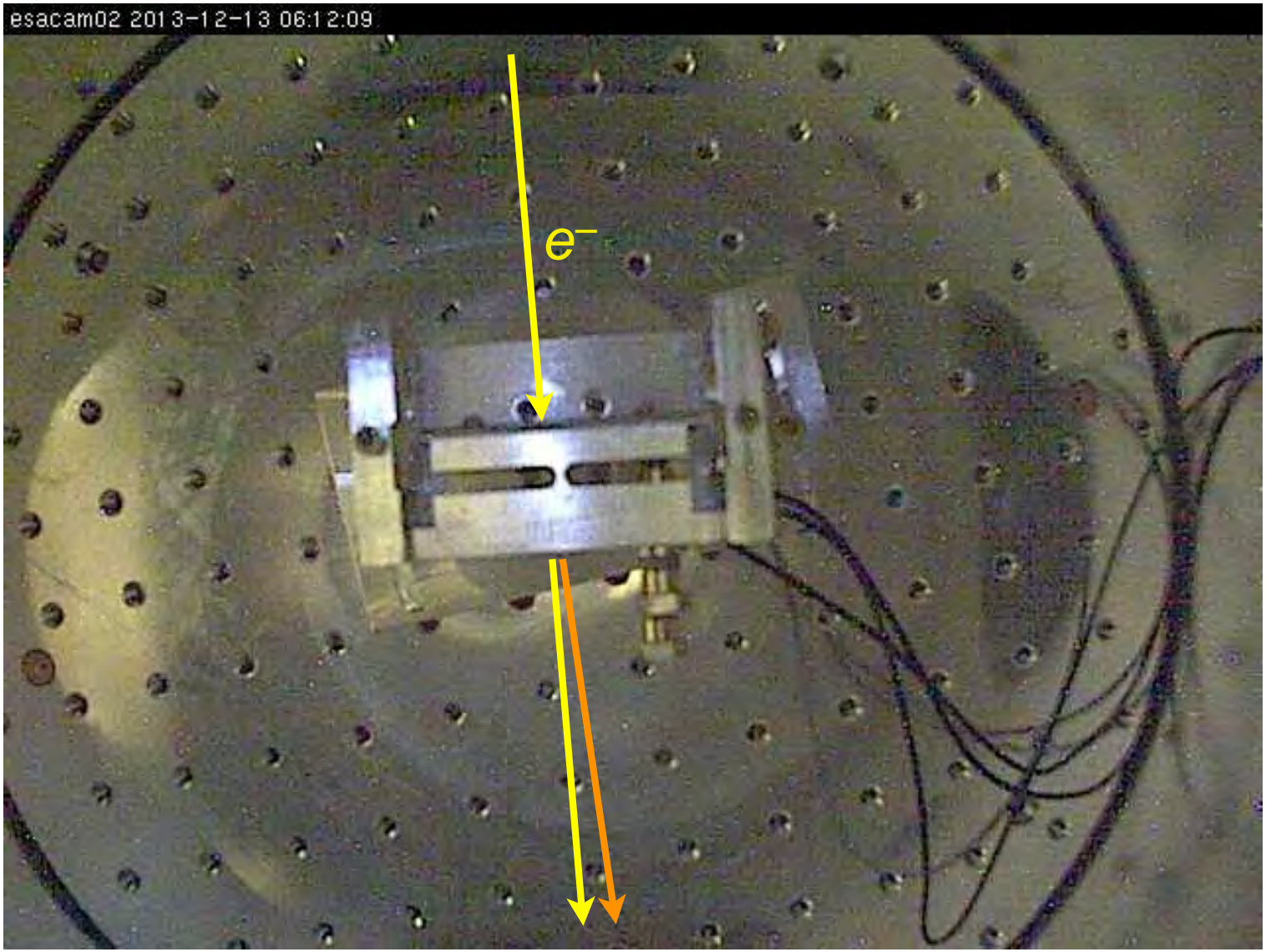


Beam finder wire installed for 1st beam

Mirror for angle readout



Crystal mounted in “Kraken” Chamber in ESA

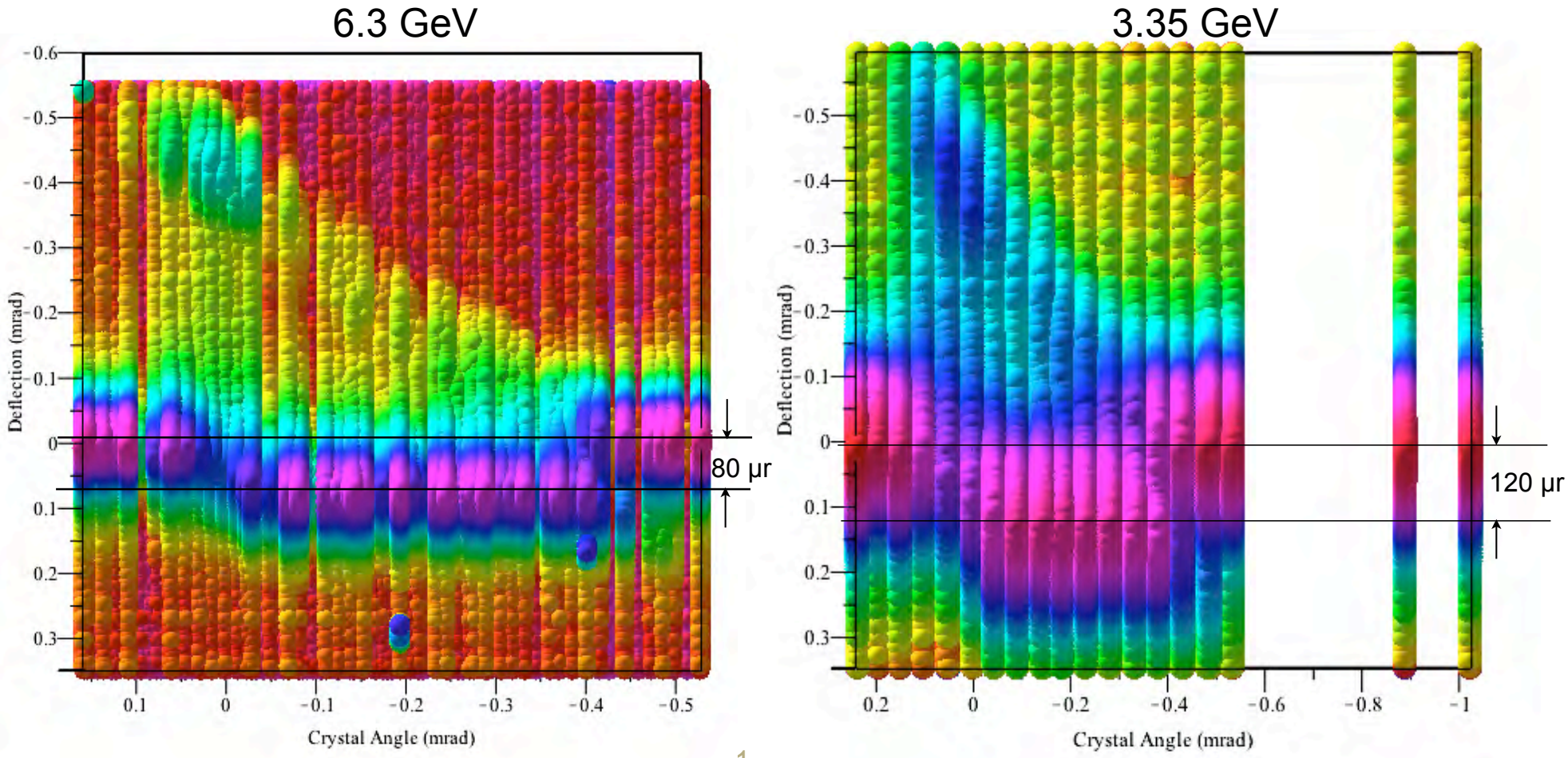


Crystal-Rotation @ 4.2 GeV

(Movie credit: T. Wistisen)

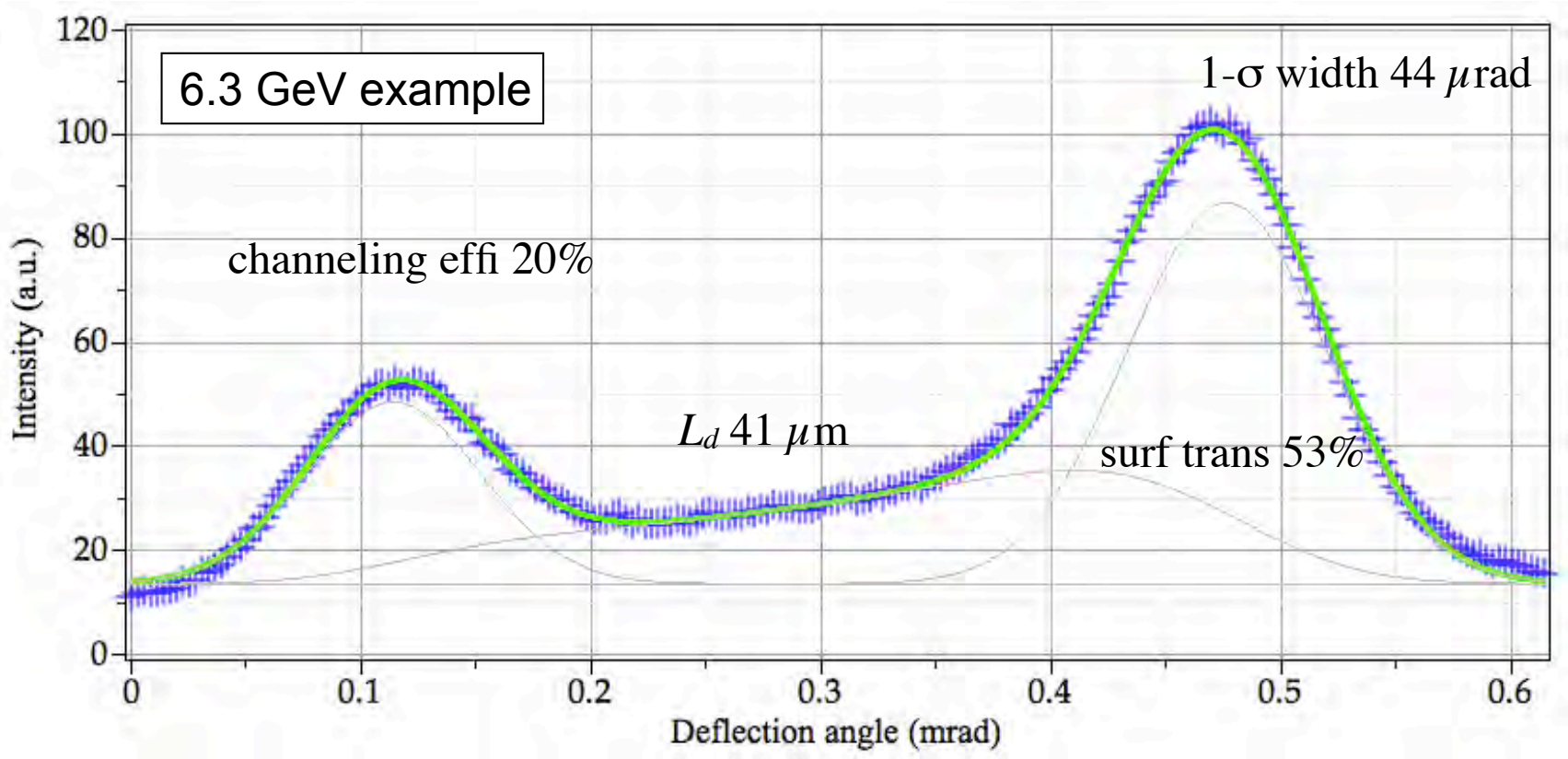
Triangle Plots

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



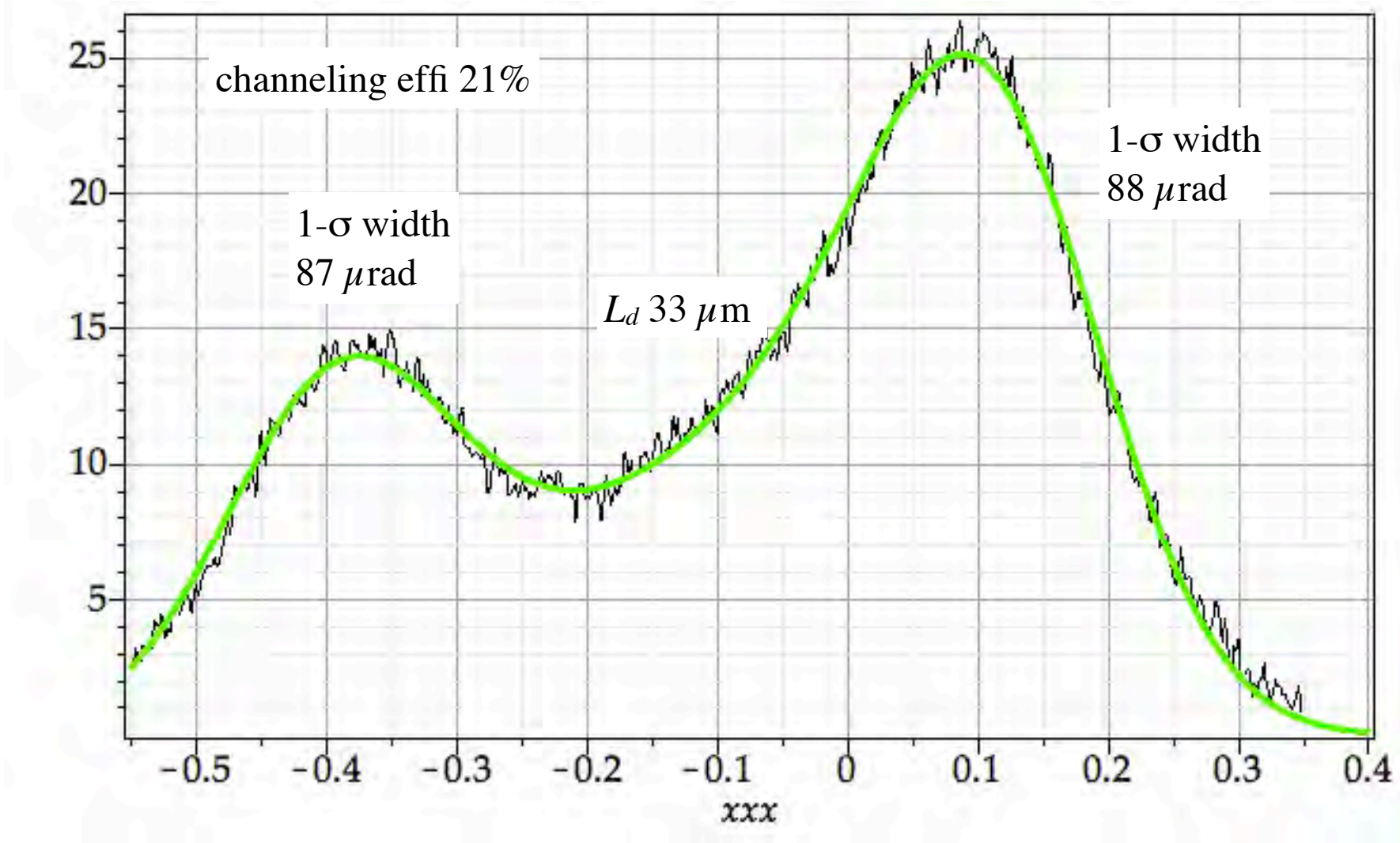
Fit to Intensity Distribution

- unfold 2 peaks + exponential dechanneling tail

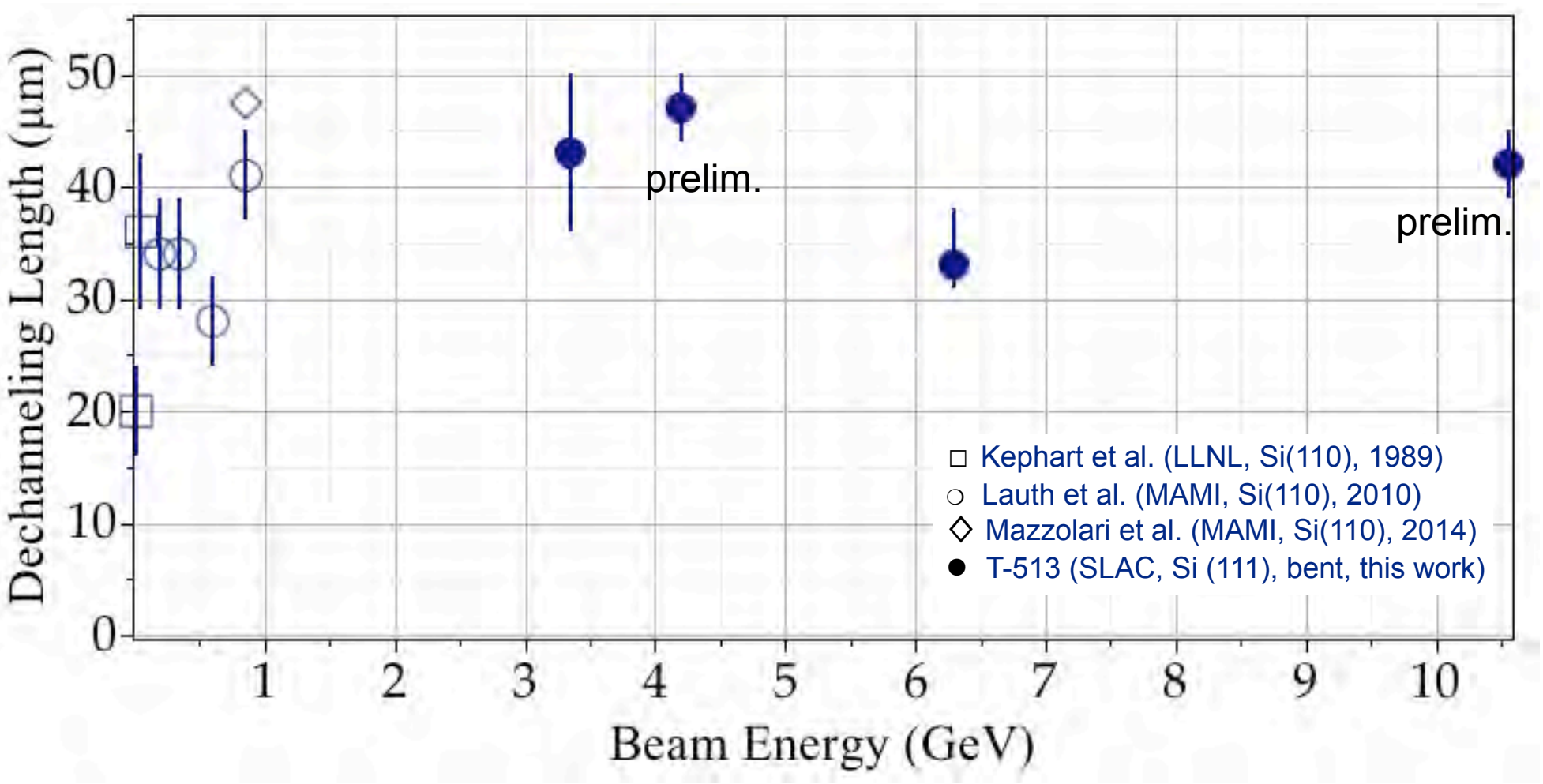


Channeling efficiency := (channeling peak)/(all)
Surface transmission := (channeling + tail)/(all)
Dechanneling Length := xi/(defl. angle) * (crystal length)

3.35 GeV Fit Example

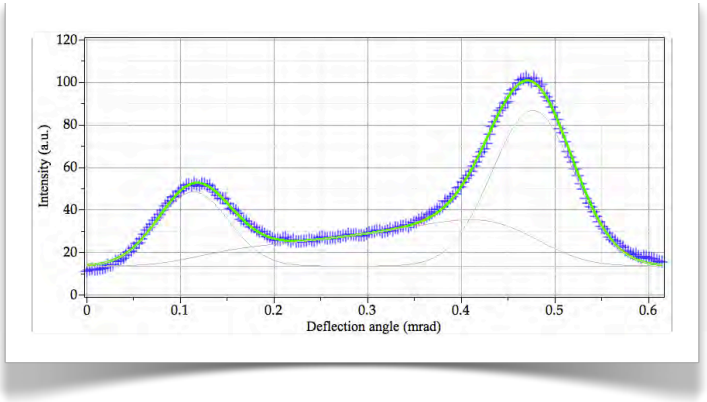


e^- Dechanneling Length Data Summary



Are the data consistent?

- Sanity check: Can we account for all intensity:
  - e.g. @ 6.3 GeV, channeling: Surface transmission 57% and dechanneling length 33 μm (≈1/2 crystal)
    - => 16% of 57% (≈ 9%) should be in the channeling peak
      - we see 23%



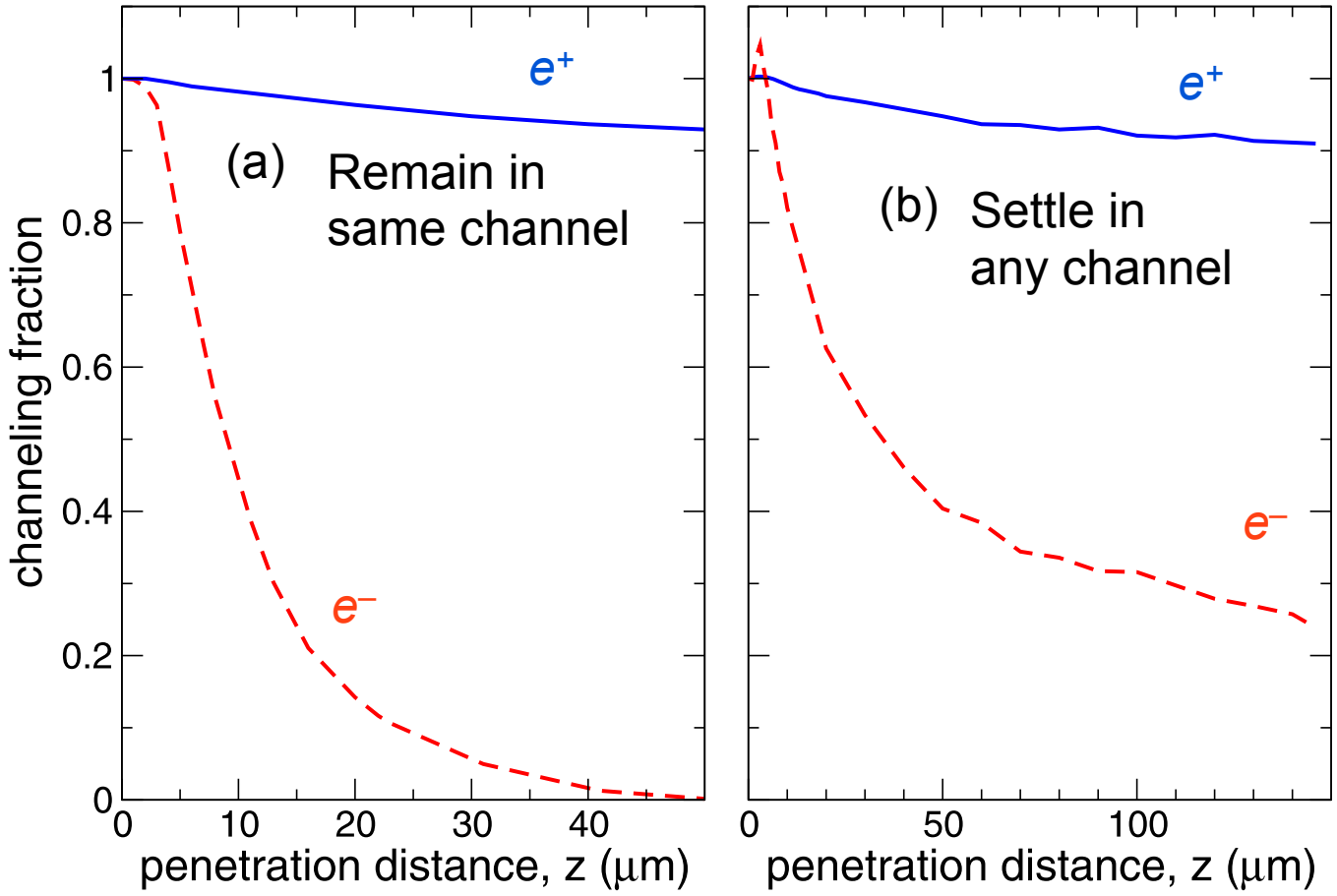
- How to resolve this discrepancy?
  - Parameter sensitivity? Unlikely at the factor-2 level
  - De-channeling model wrong?
    - Rechanneling ?(see e.g. model of Sushko et al.)

Dechanneling estimates (Sushko et al., 2013)

G.B. Sushko et al., J. Comp. Phys. 252, 404-418 (2013)

855 MeV beam, (110) Si, straight. Case (b) can be fitted with two exponentials, dechanneling lengths would be 16.8 μm and 223 μm.

What do our data suggest?



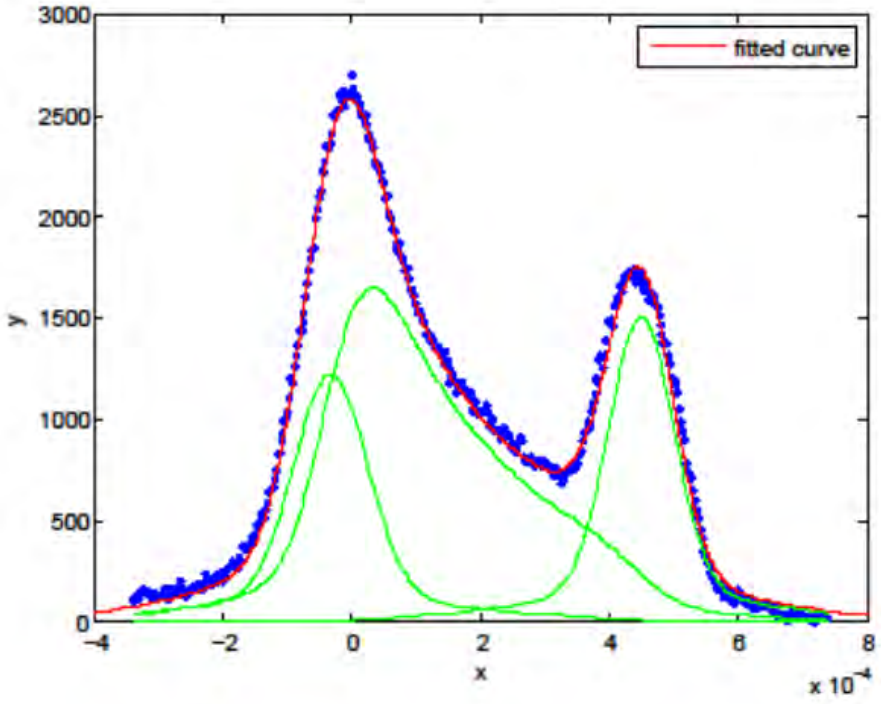
Unfolding Two-Dechanneling-Lengths (Wistisen)

$$P(\theta) = Ae^{-\frac{\theta}{\theta_{D1}}} + (1-A)e^{-\frac{\theta}{\theta_{D2}}}$$

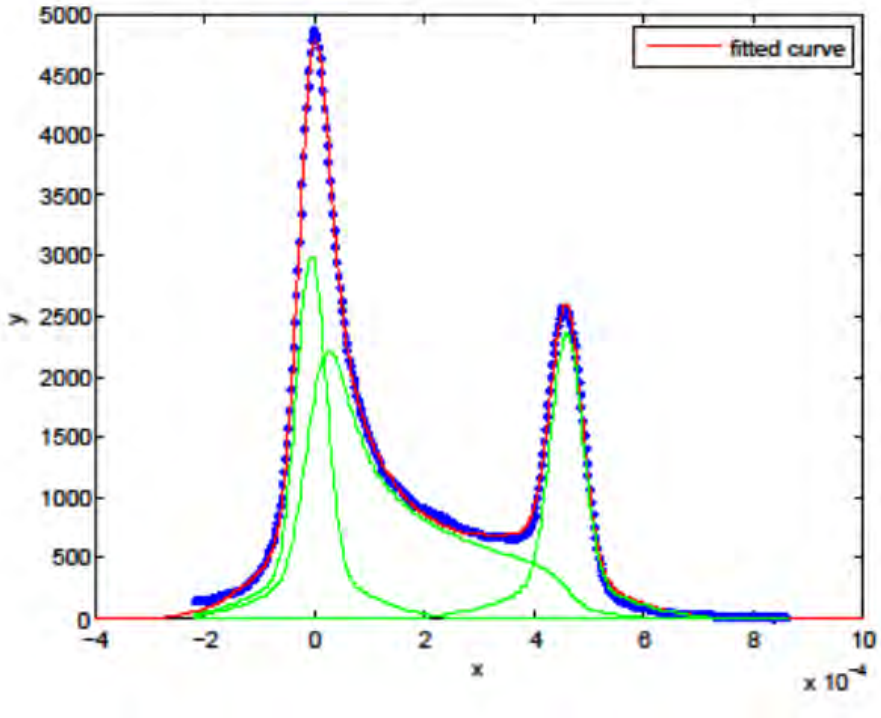
- L_{D1}=30 μm, L_{D2}="long" for 4.2 GeV data
- L_{D1}=6.9 μm, L_{D2}=75 μm for 10.5 GeV data…???

Very preliminary! Final conclusion not yet clear

4.2 GeV

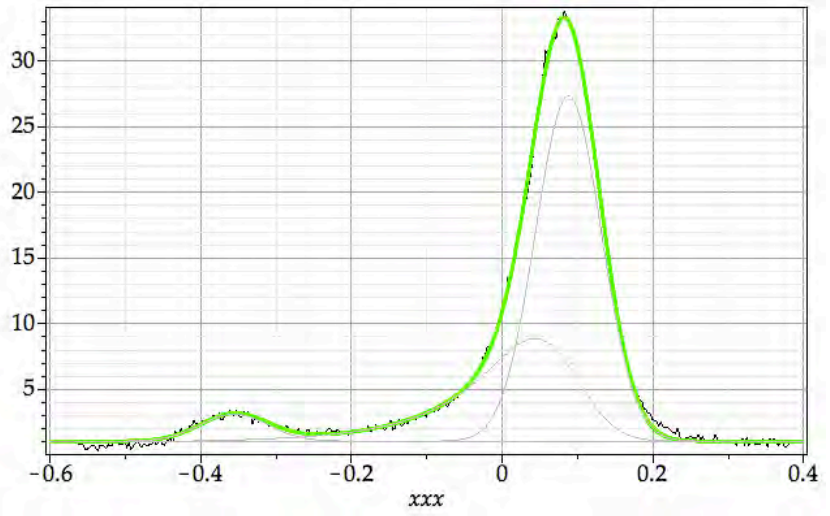


10.5 GeV

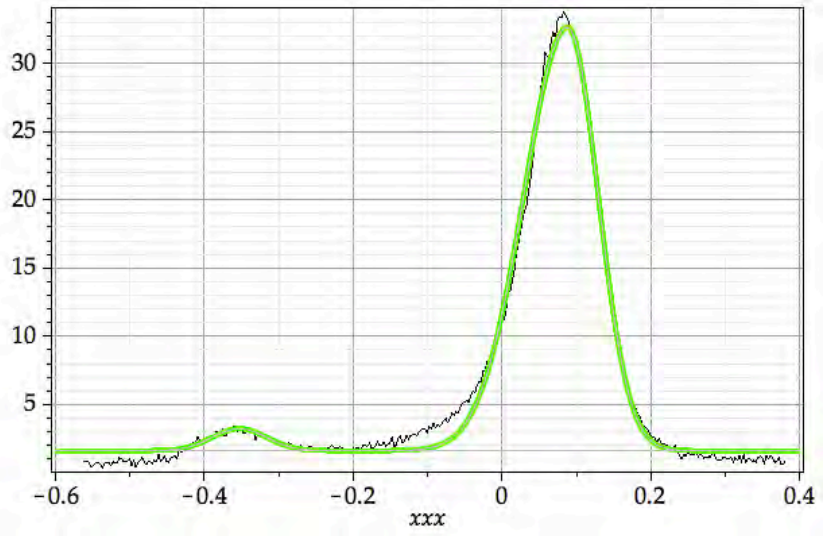


VR Efficiency (6.3 GeV)

- Fit with “universal function”
  - VR efficiency (main/all) is 63%.



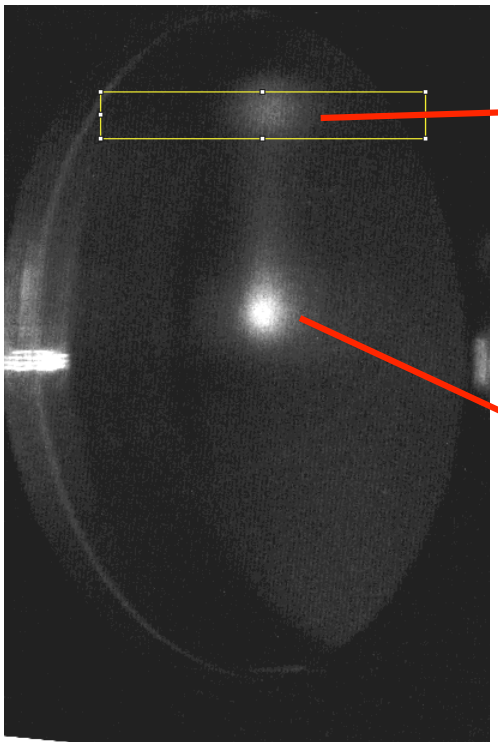
- Fit with asymmetric Gaussians
  - VR efficiency (main/both) is 96%.

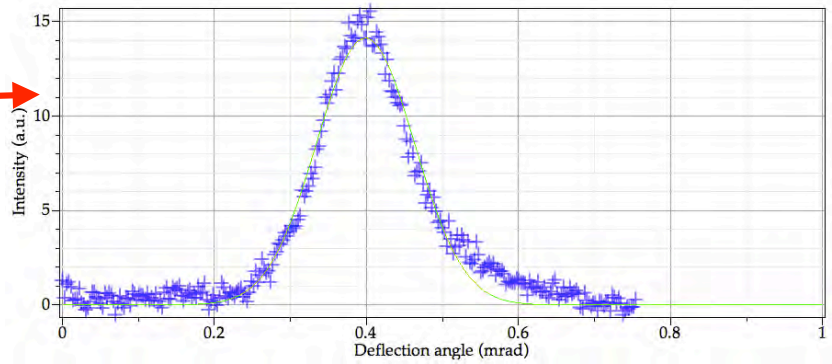


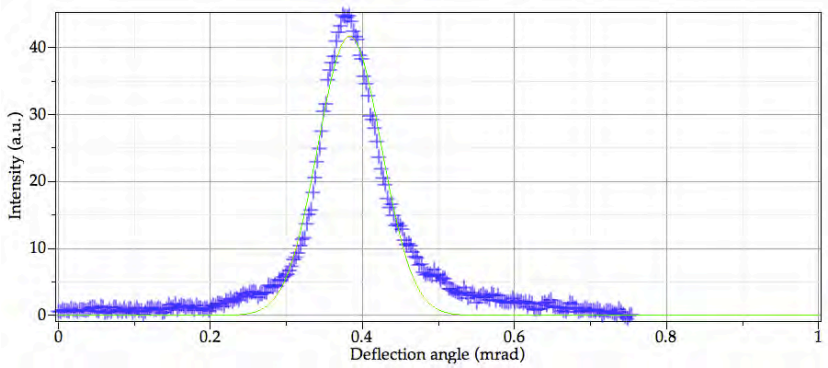
- ≈ 90% with deflection >0

Scattering of Channeled Beam

- Divergence widened by almost 1.5 in channeling (6.3 GeV)







Scattering of Channeled Beam *vs* Energy

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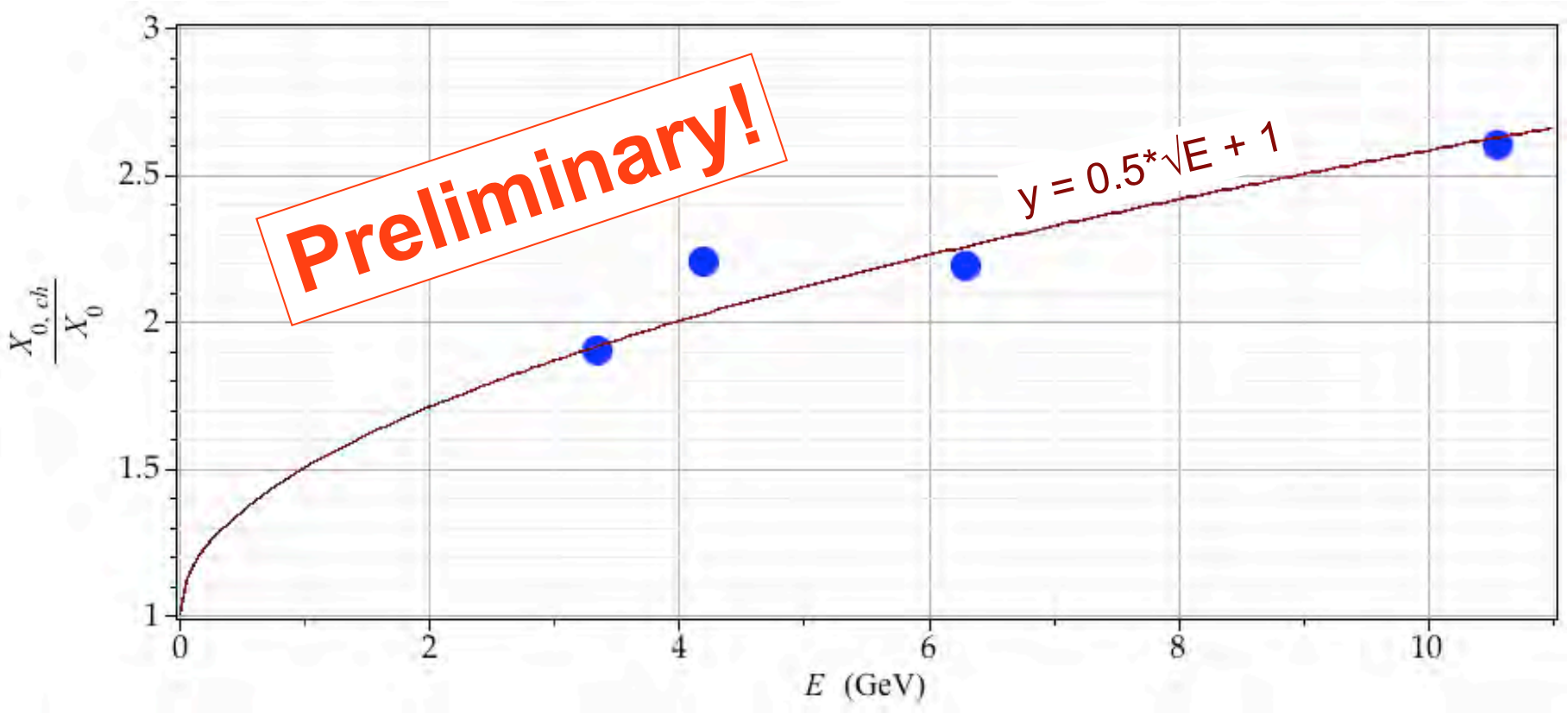
- Widening of channeled beam/main beam
  - if multiple scattering, use modification of X_0 to parametrize
  - suggestive of √E relation, but not enough data to make claim



Summary of T513 Results

- Channeling efficiency ≈ 22 %, VR up to 95%
- Dechanneling length ≈ 30…40 μm
  - seem to be relatively independent of the beam energy
  - data suggest 2^{nd} component, nearly flat, re-channeling effect?
- 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
  - In units of X_0: Factor 1.9 @ 3.35 GeV, 2.6 @ 10.5 GeV
    - positive correlation with √energy
- Sufficient data to e.g. simulate crystal in a beam-collimation scenario.

E212

SLAC

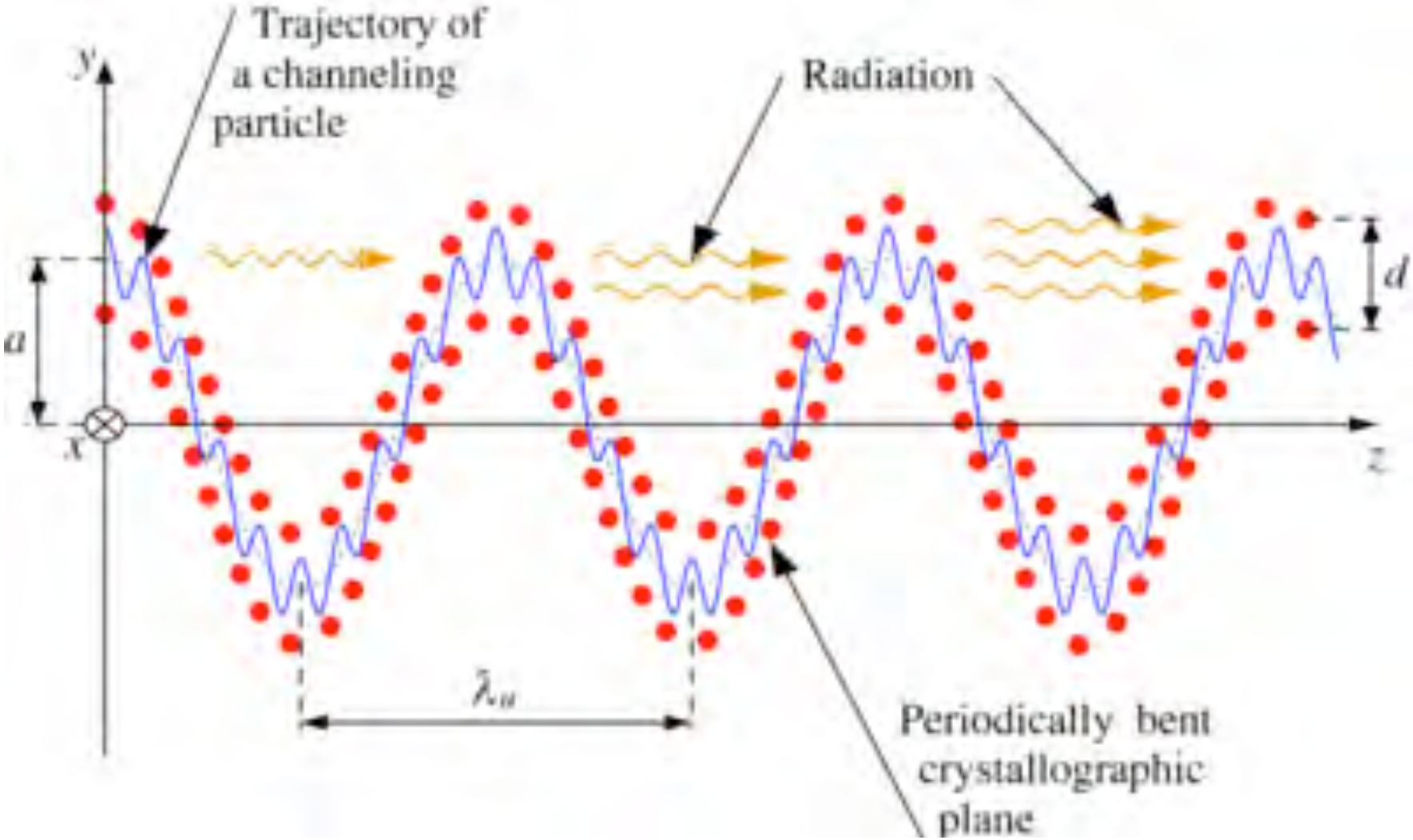
- "Radiation from GeV electrons in diamond – with intensities approaching the amplified radiation regime" (Uggerhøj et al.)

- E212 just had its first run (with e^+)
  - 10-period undulator, 4 μm long; looking for γ peak 6…8 GeV
  - T513 crystal also in chamber (backup and test object)
    - Critical angle ≈ 40 murad
    - m-scattering angle (rms) ≈ 12.5 murad

- Determine γ energy by spectroscopy of positrons
  - FACET spectrometer well suited
  - Intensity of radiation low due to thin crystal => challenge

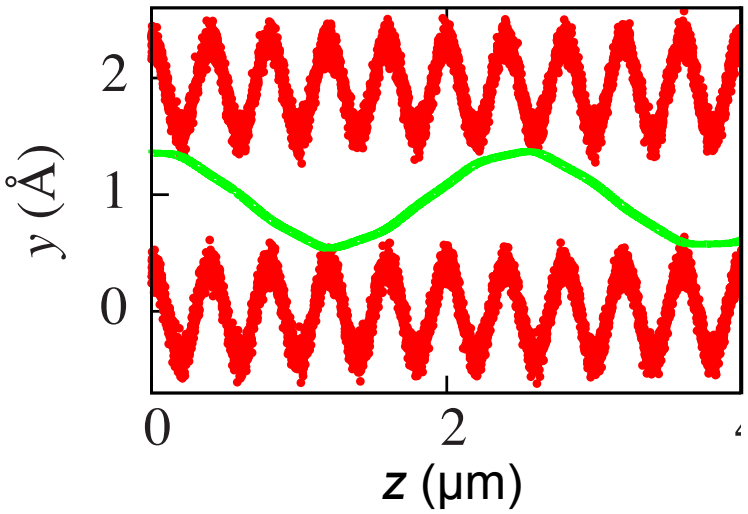
Crystal Undulator (Solov'yov, Korol, Greiner et al.)

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

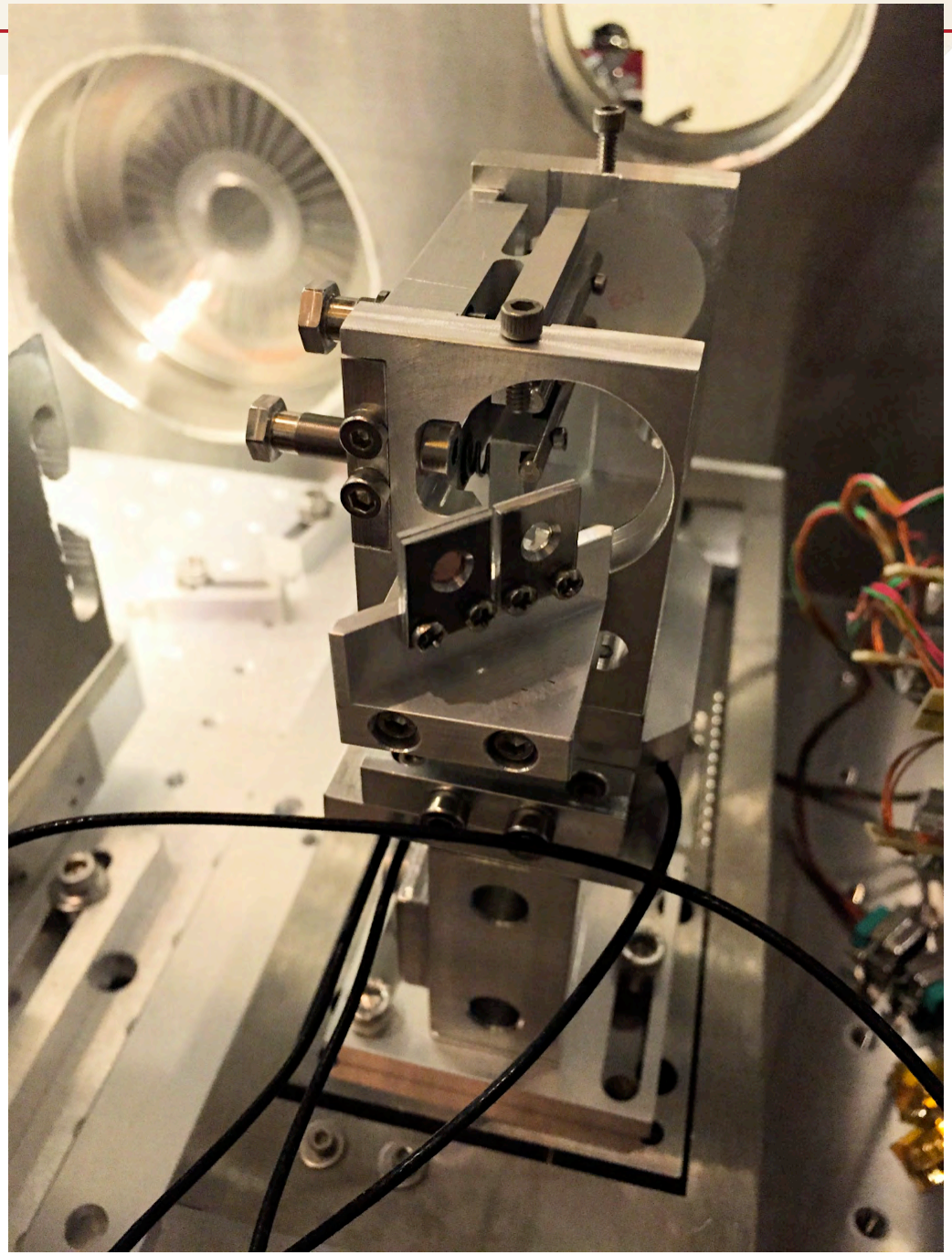


Kostyuk Undulator

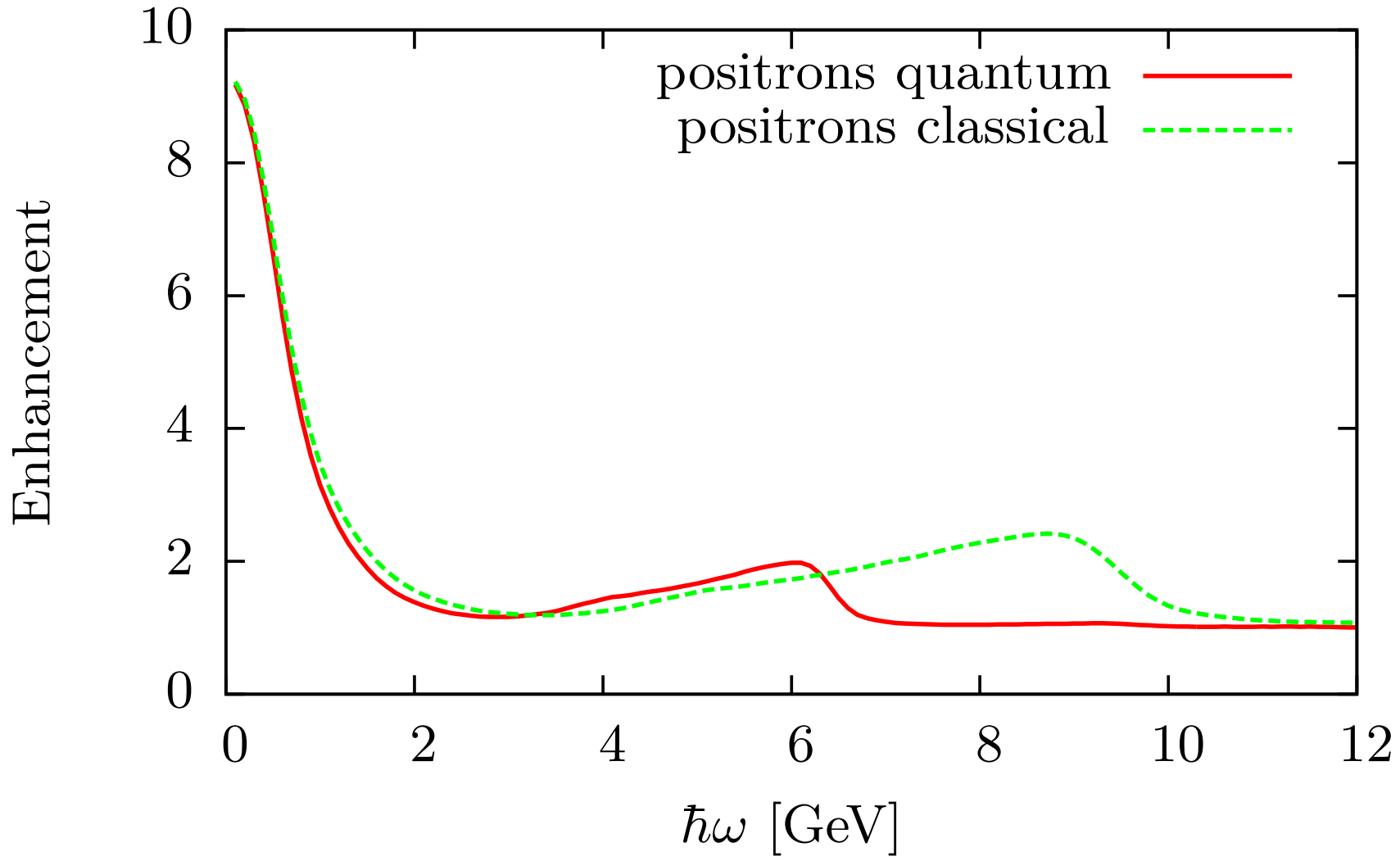
- "Slow" betatron oscillations, fast undulations
  - Undulator period < betatron period
  - supposed to work with electrons as well.
- E212 undulator: strained lattice Si (111) crystal
  - variable doping with Ge creates undulations
  - 4 μm long, 10 periods



E212 Crystal Assy in Chamber

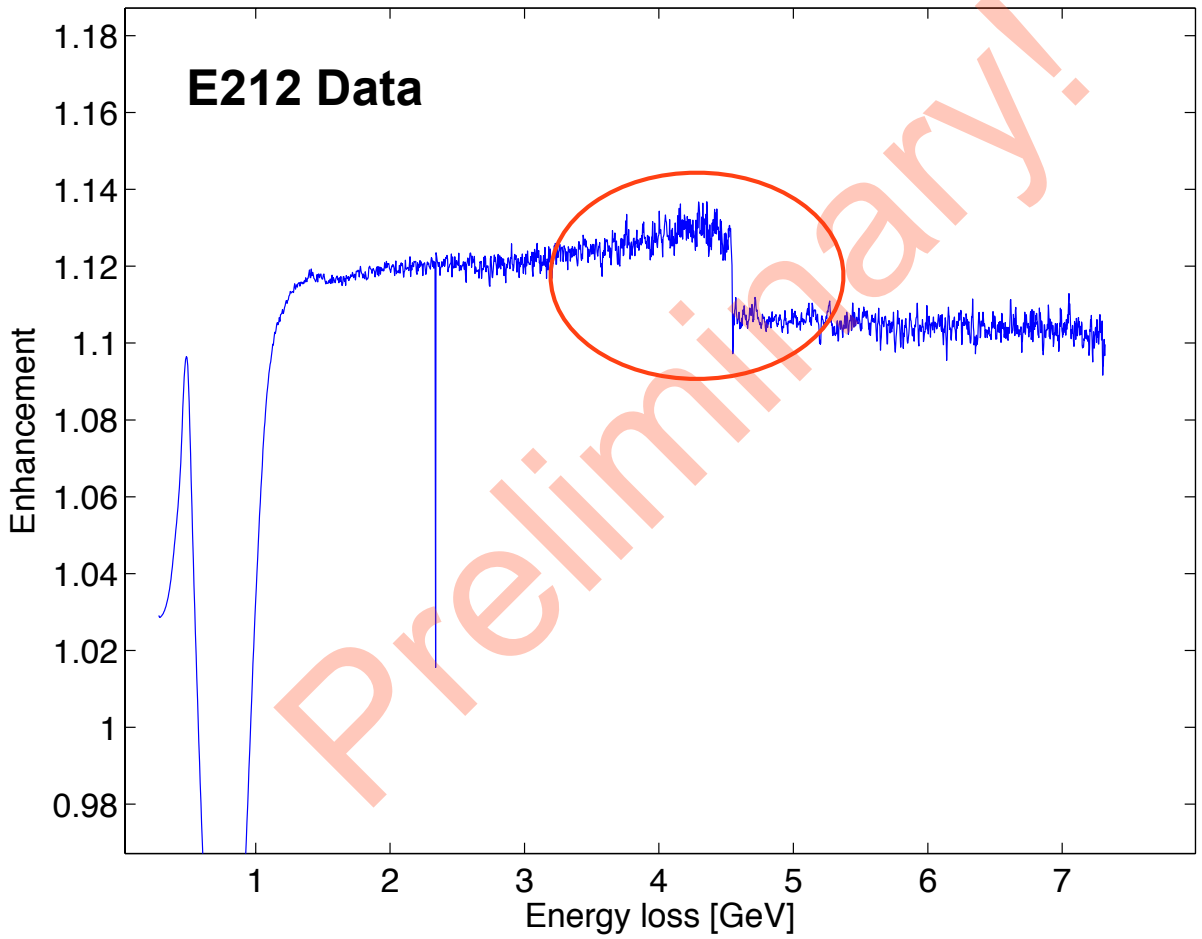


Expected Power Spectrum over B-H (flat)



E212: First Data from Undulator in Channeling

We saw a repeatable radiation signal when rotating crystal
Spectrum below is electron energy-loss power spectrum
Feature is likely *not* undulator radiation



E212: First Channeling Data of e+ in Bent Crystal

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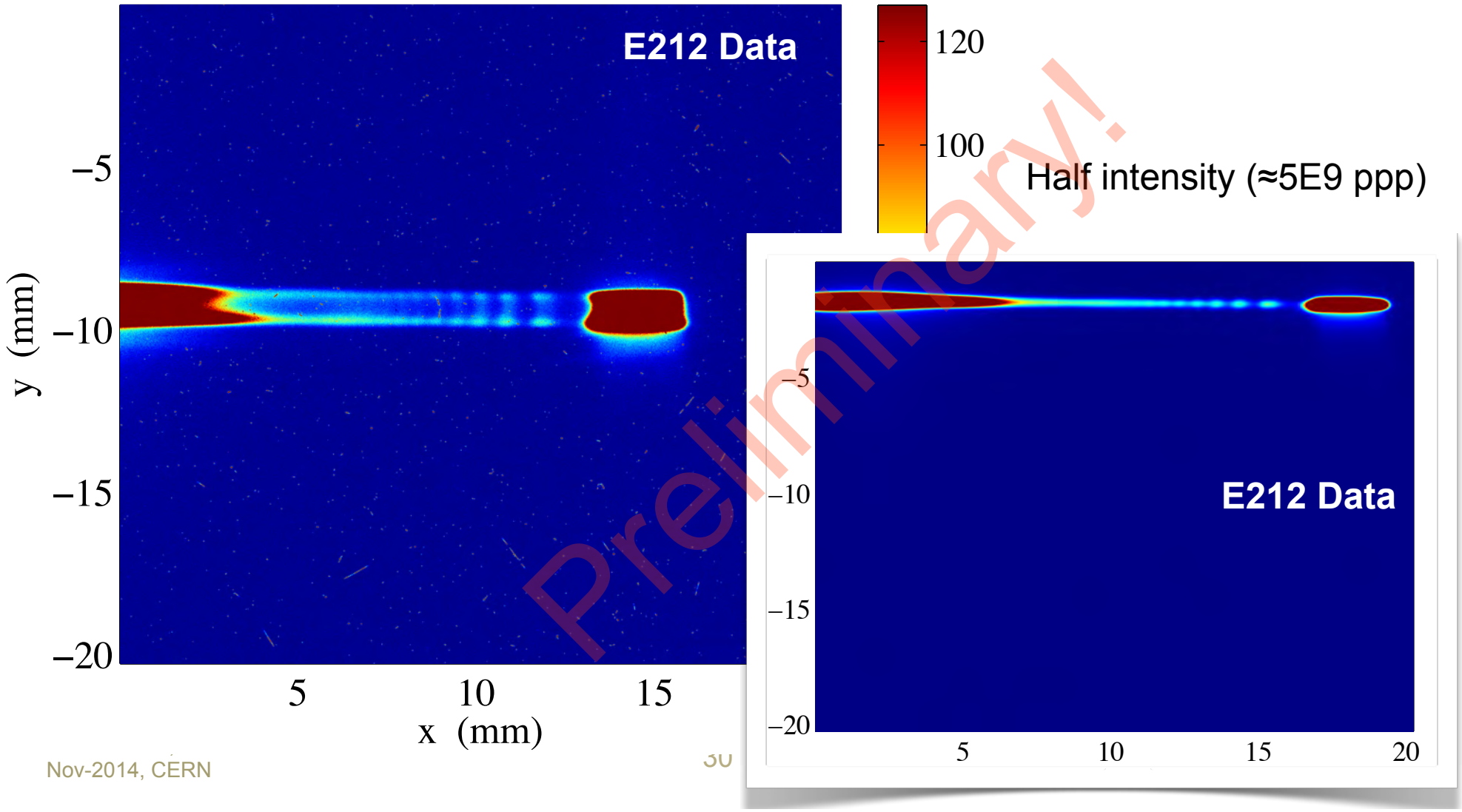
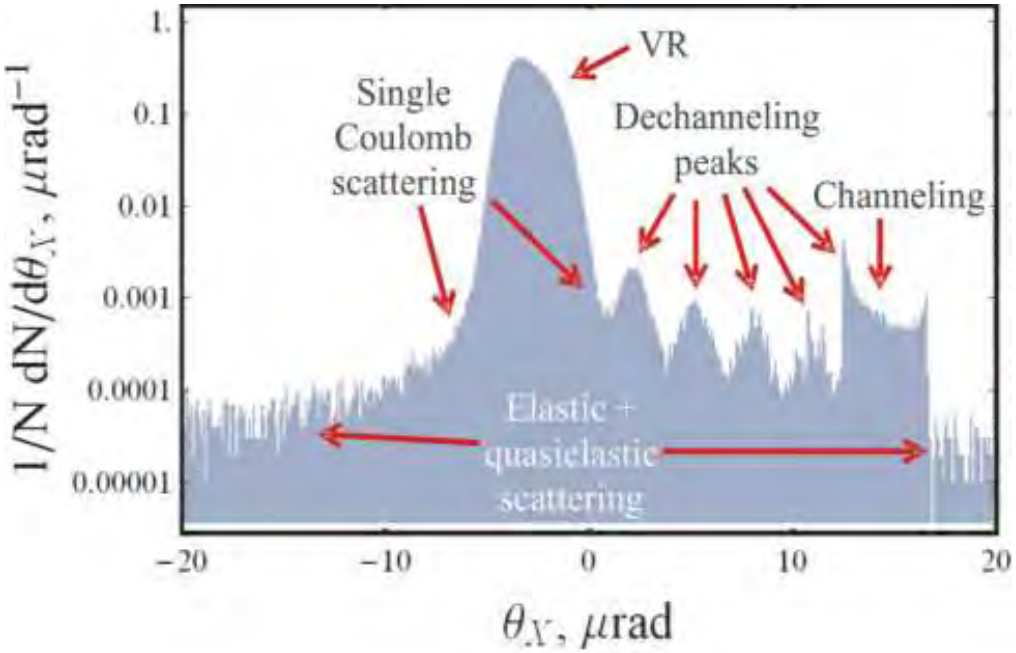
- Raw data, preliminary

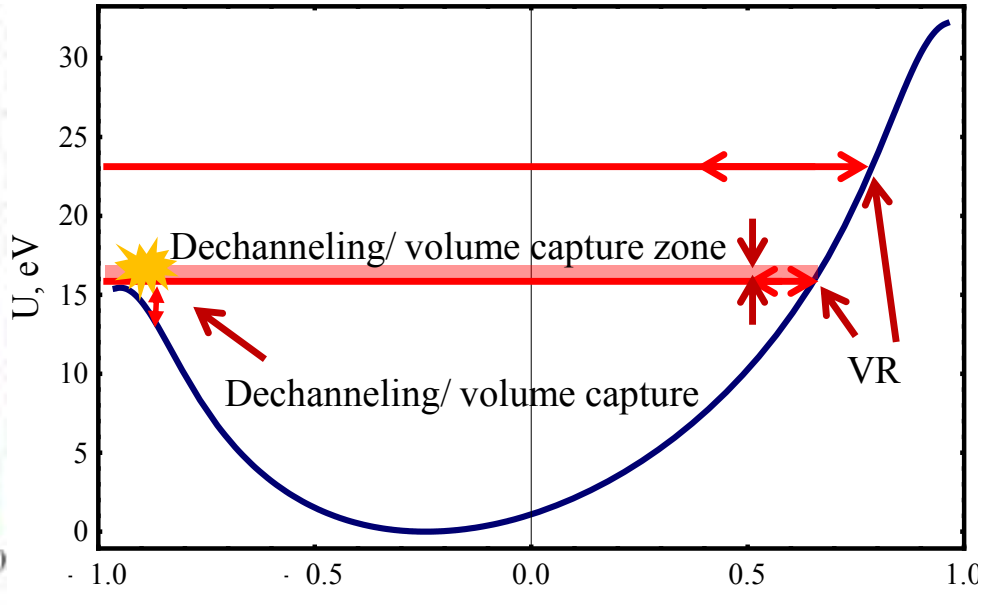


Ripples predicted by Sytov & Tikhomirov

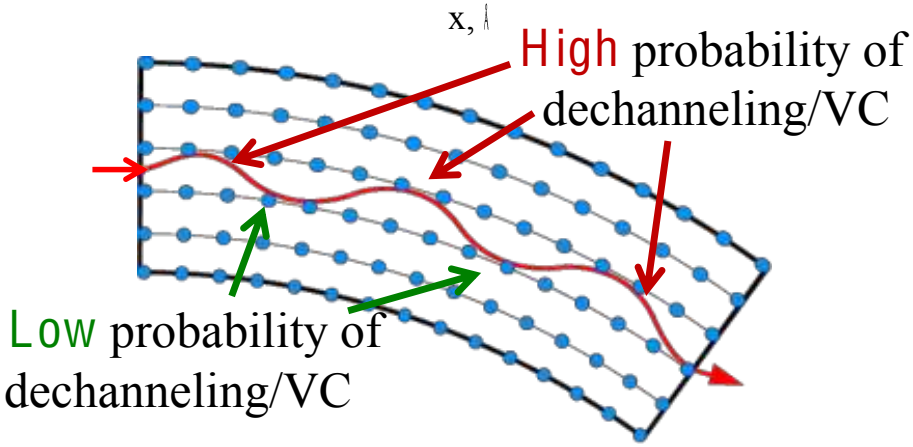
Deflection angle distribution



Interplanar potential in a crystal with R=80m, (110)



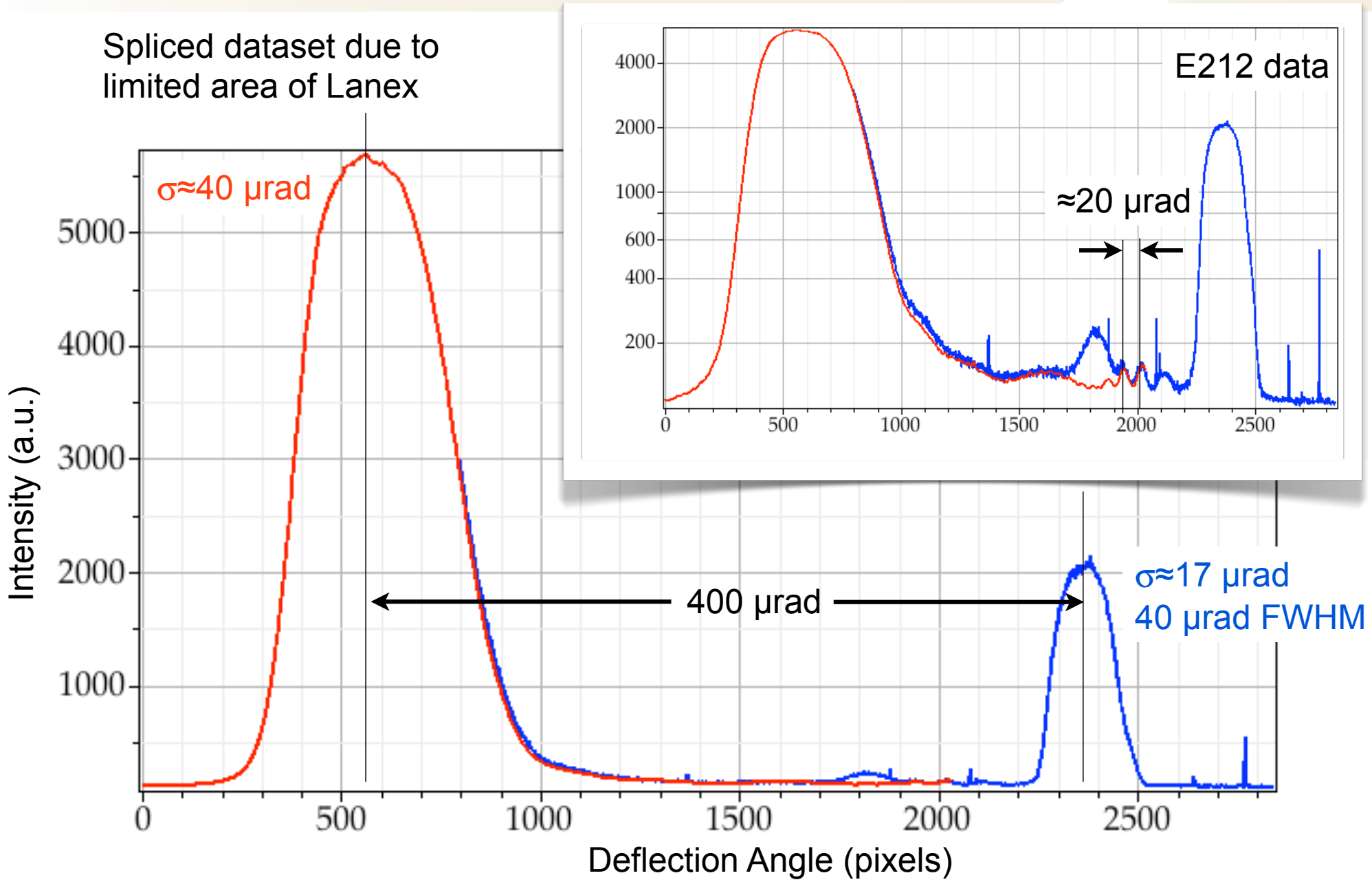
Dechanneling peaks appearance condition:
Scattering angle* on the crystal less than the peak half width:



Sytov & Tikhomirov, Channeling 2014, Capri

Expect to see this @ LHC

Intensity Profile



E212 Summary (Very Preliminary)

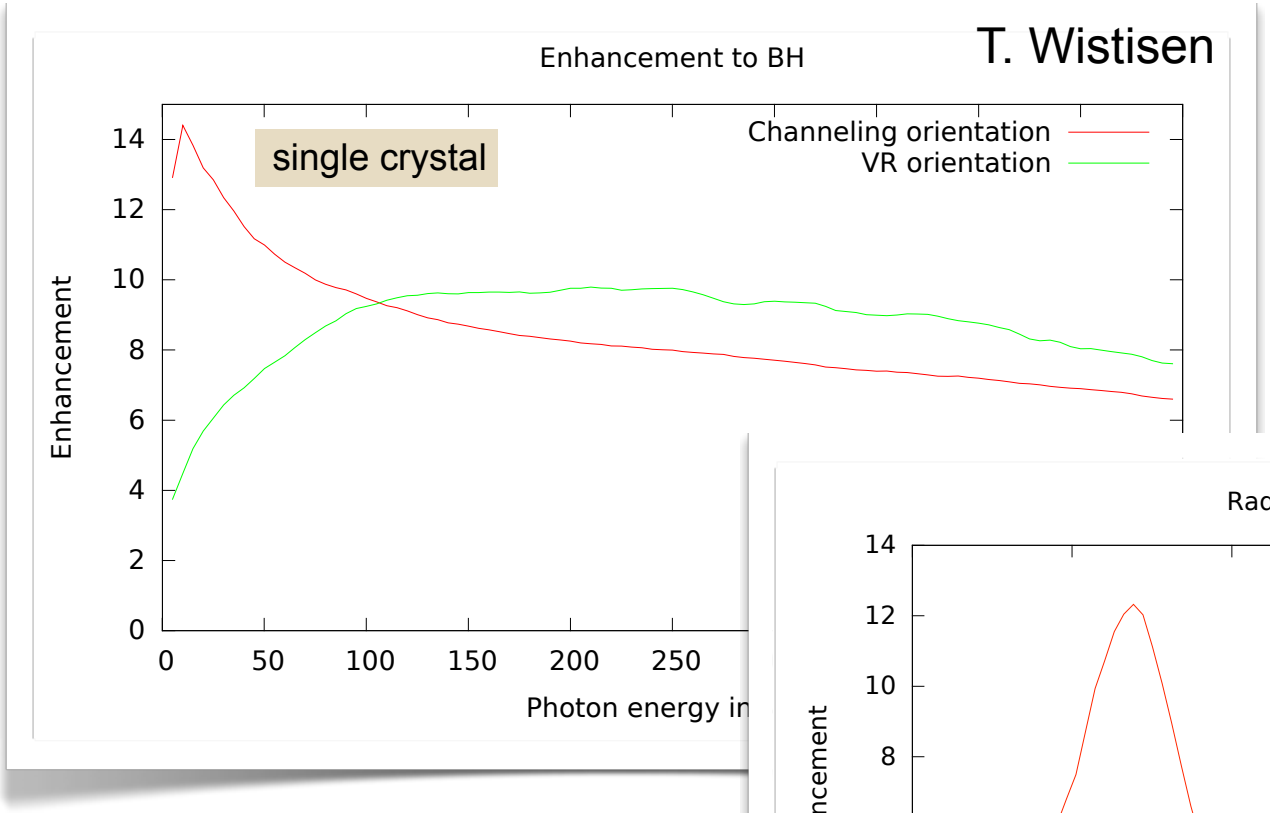
- Evidence for “ripples” in dechanneling tail, predicted by Sytov & Tikhomirov (for LHC-energy protons)
- Dechanneling tail very faint => long dechanneling length
- Channeling peak maybe 40% of VR peak… surface transmission?
- We have data for the full triangle, awaiting analysis.
-

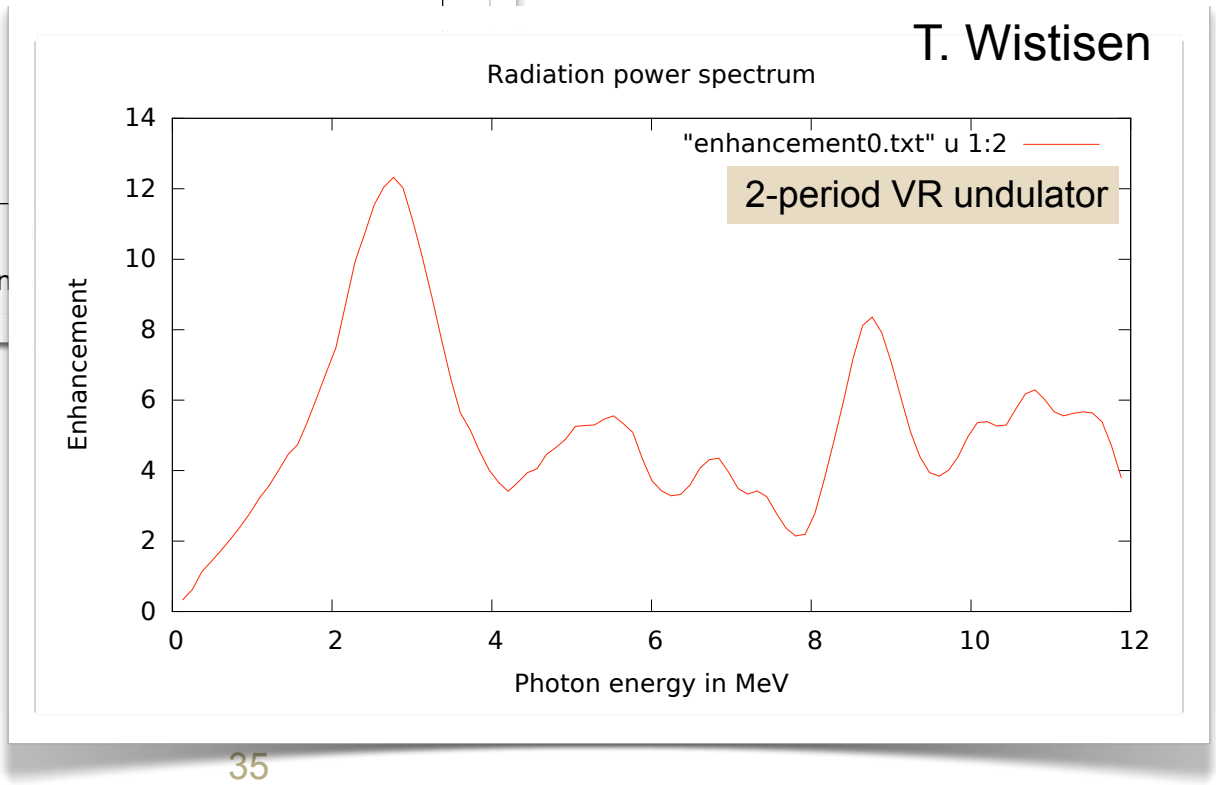
Plans T513 (ESTB)

SLAC

- There are two somewhat separate thrusts of T-513 successor experiments:
  - **e^- Beam collimation demonstration using a VR array**
    - Expect to gain by $\sqrt{n}$ over single crystal
    - Conceptually simple experiment but needs new crystals
      - good right at the edge
    - Additional stages being bought
  - **Radiation generation, characterize channeling and VR radiation (T523).**
    - T-513 crystal suitable for first exploration
    - need to come up with a suitable γ-ray detector.
    - Goal: VR Undulator

Radiation Spectrum (6.3 GeV e^-)





Plans E212 (FACET)

- The thrust of E212 is the generation of coherent gamma radiation at high intensity.
  - WIth an undulator crystal and high charge-density positrons, might see amplification.
- Next step will be using a longer-period undulator and a gamma spectrometer
  - MeV gamma rays, using Compton scattering to analyse.
- Also, a matching set of electron and positron data @ 20 GeV with bent crystal is highly desirable.

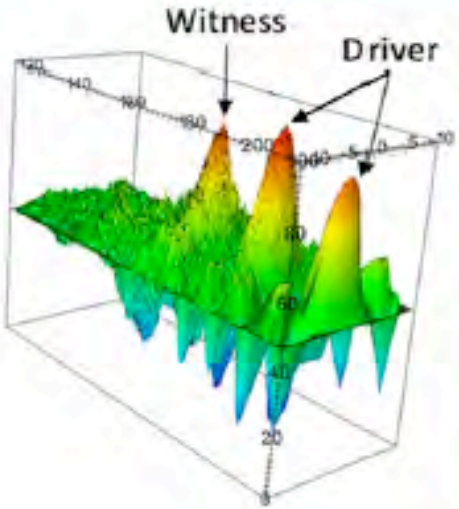
THEXAC

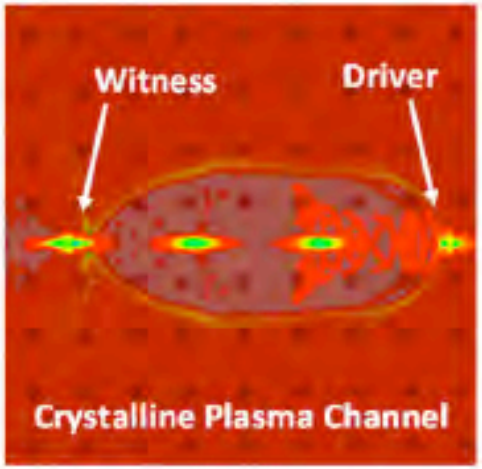
SLAC

- Some of us are getting involved in the THEXAC acceleration proposal by T. Tajima et al. (Transformative High Energy X-ray Acceleration in Crystals).
  - Exploration of wake-fields in crystals with possibility of acceleration
  - Ultimately requires PW laser at O(10 keV) energy
    - possibly to be generated at ELI-NP (Romania)
  - FACET can examine intensity-related effects that need to be demonstrated and understood to be able to determine feasibility.

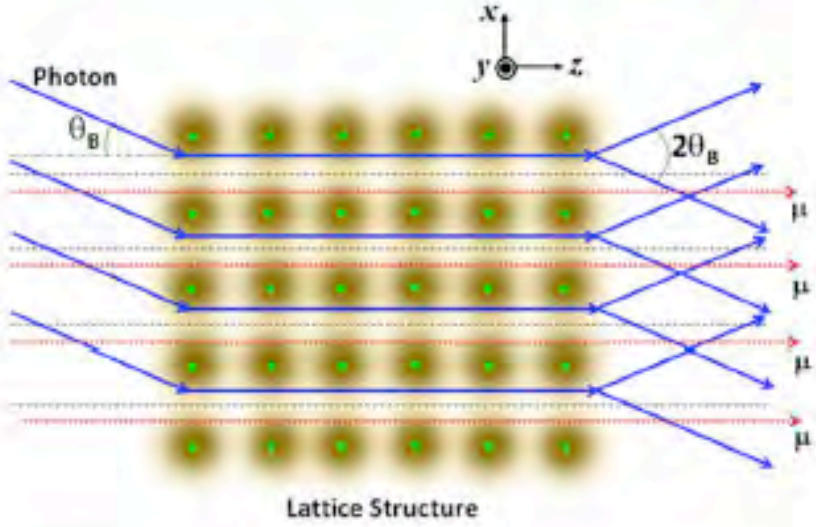
Wakefield excitation by electron (or positron) beam (vs. by X-ray pulse)

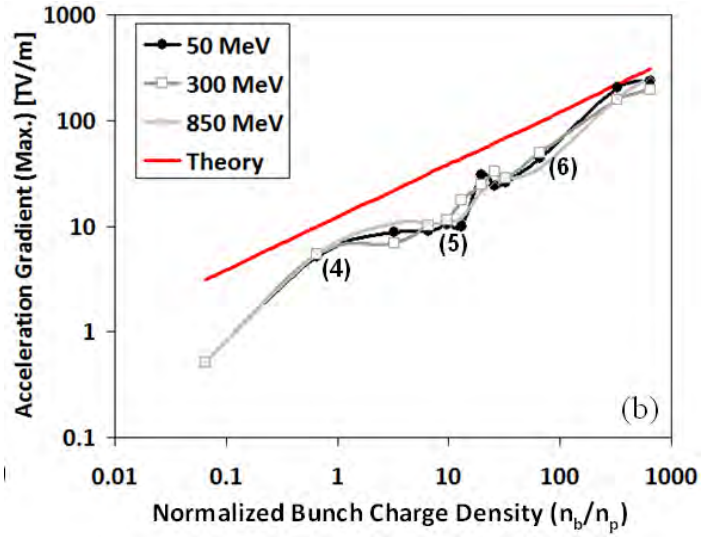
Wakefield Acceleration

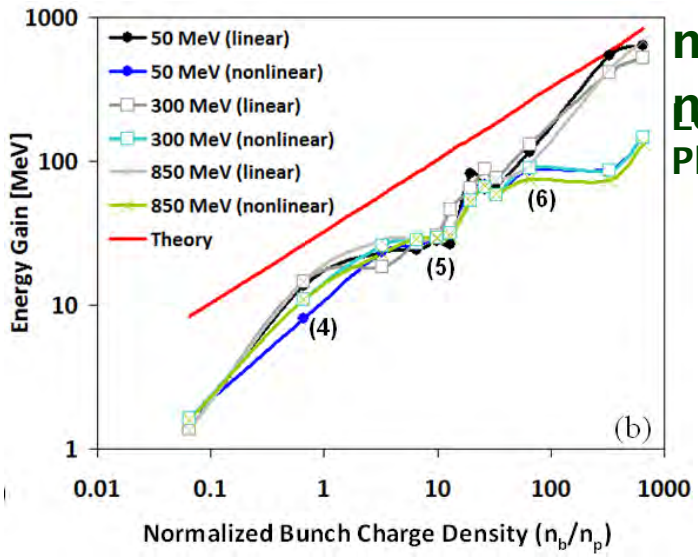




Diffraction Acceleration







$n_p = 10^{28}$ m^{-3}

Length of Plasma = 10 λ_p

Y.M. Shin (2014)

Conclusion

- T513 successfull beyond our initial expectations
  - First quantitative data for multi-GeV electron beam
  - surprising channeling and VR efficiency.
- E212 has produced a stunning confirmation of the dechanneling ripples predicted.
  - The Ferrara crystal continues to amaze us!
- Still looking for the signal from the Kostyuk undulator with 20 GeV positrons.
- Collaboration is steadily gaining momentum