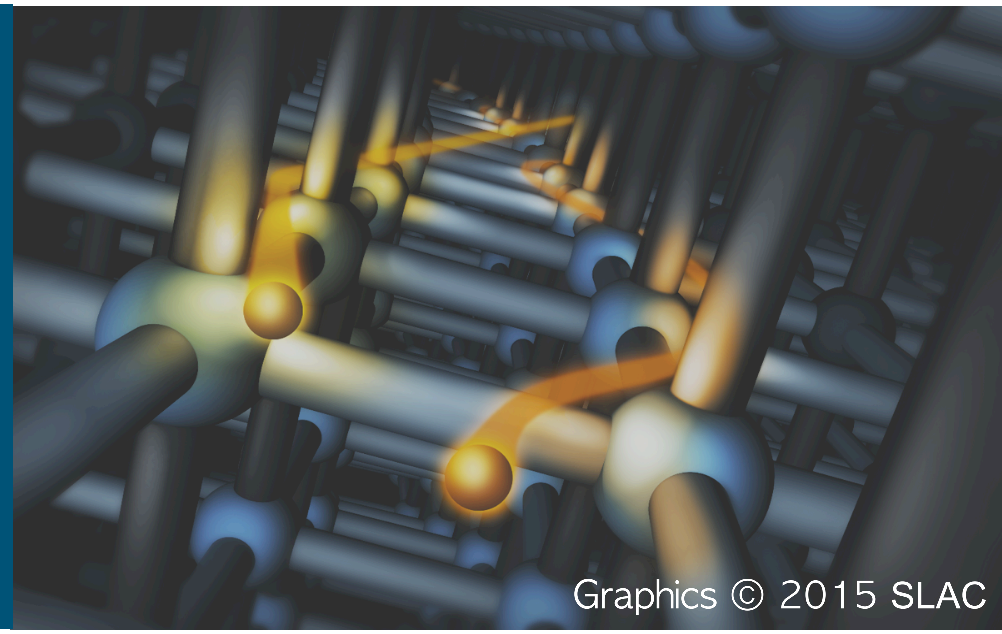
Crystal Experiments at SLAC FACET and ESTB



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R. Holtzapple, S. Tucker*, K. McArdle* (California Polytechnic State University)

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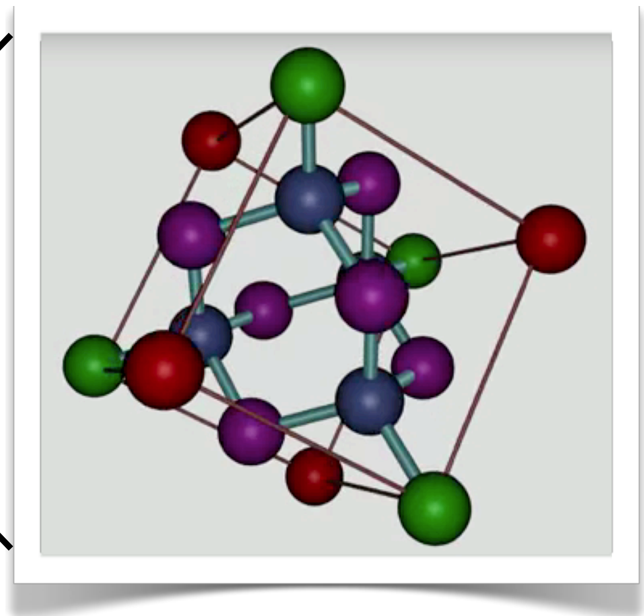
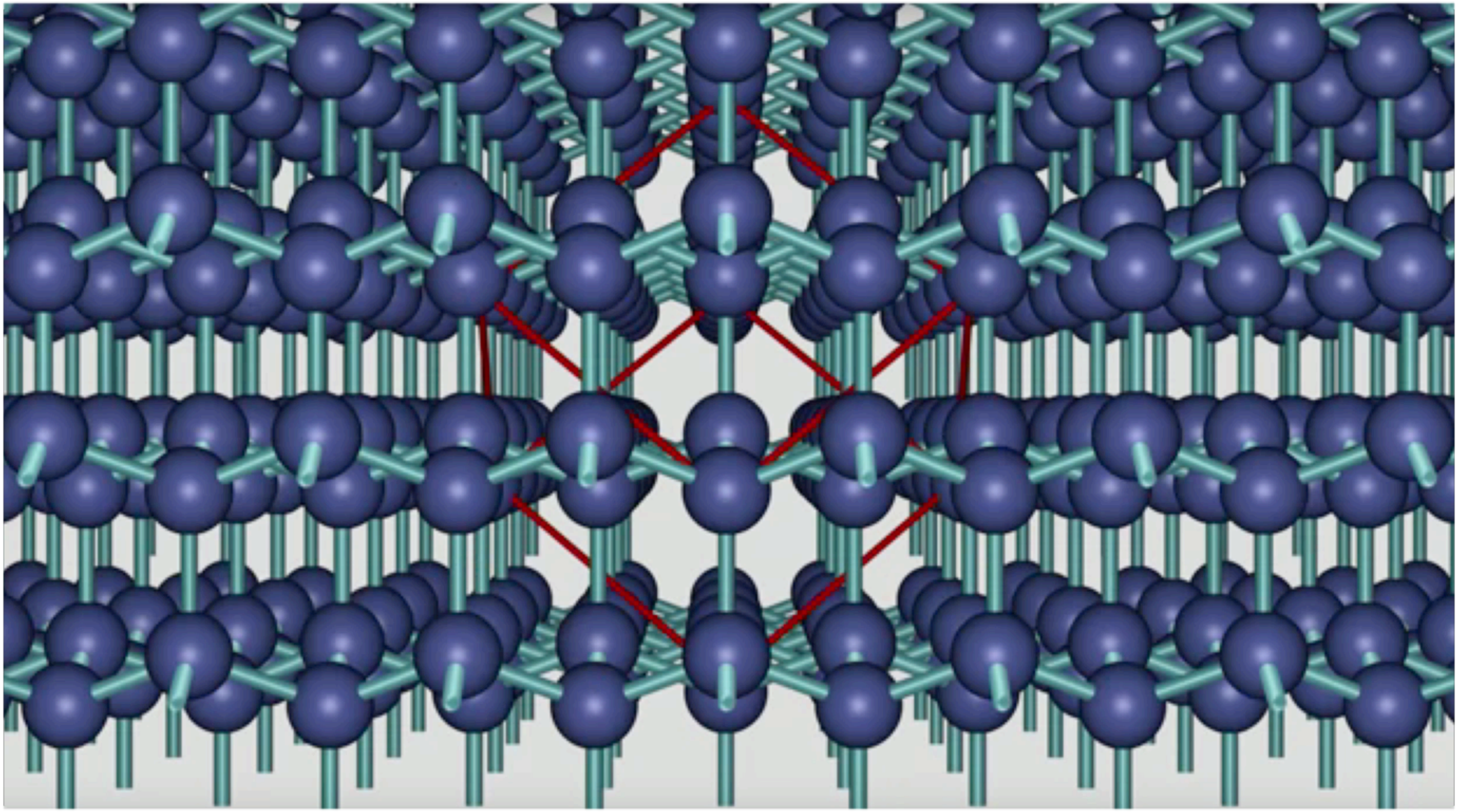
Crystalline Potentials

Si crystals

Si unit cell



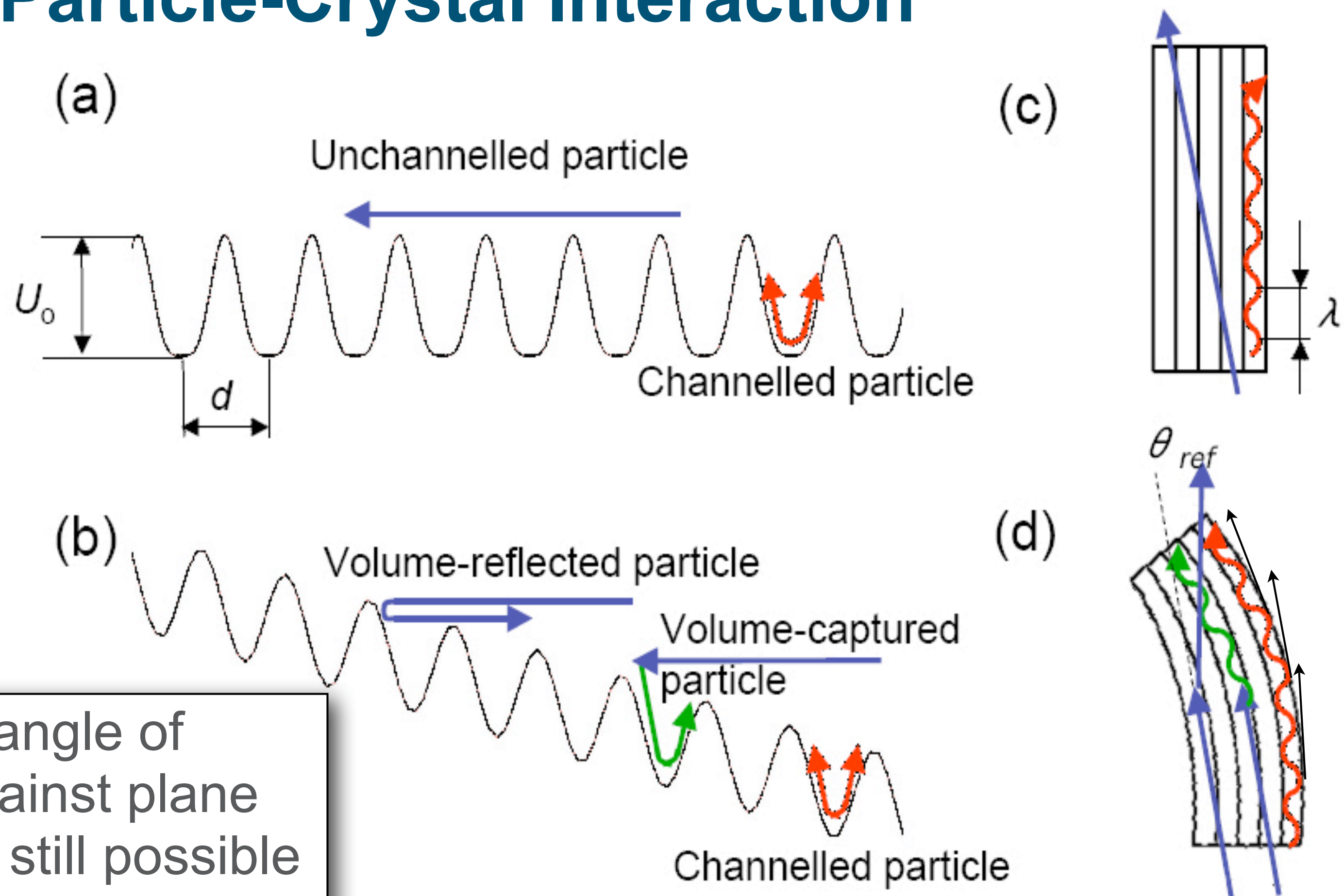
Si (111) Planes



Particle-Crystal Interaction

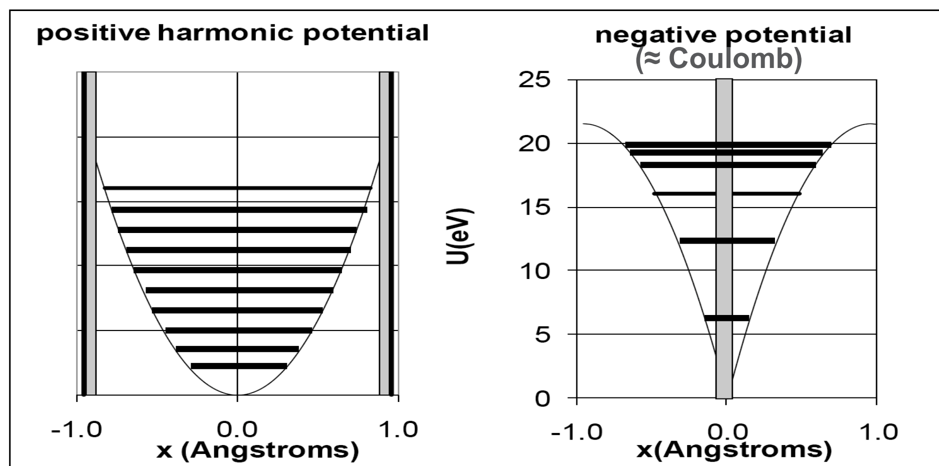
Possible processes:

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



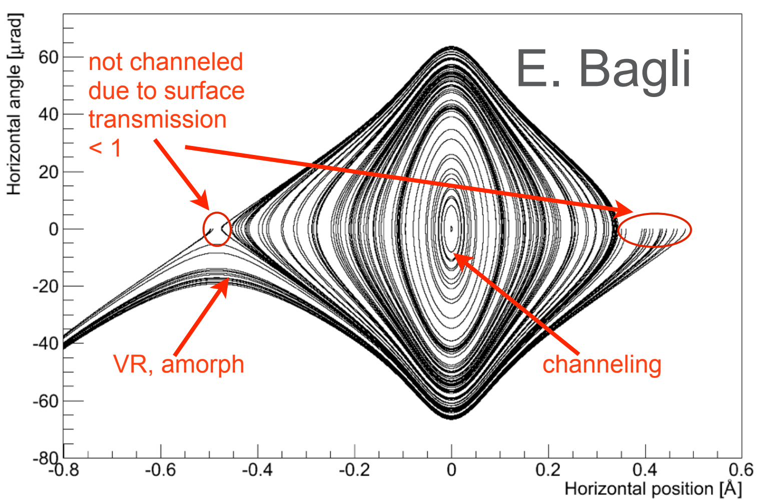
Critical angle: max. angle of incoming particle against plane where channeling is still possible
$\theta_{crit} = \sqrt{2U_0/E}$

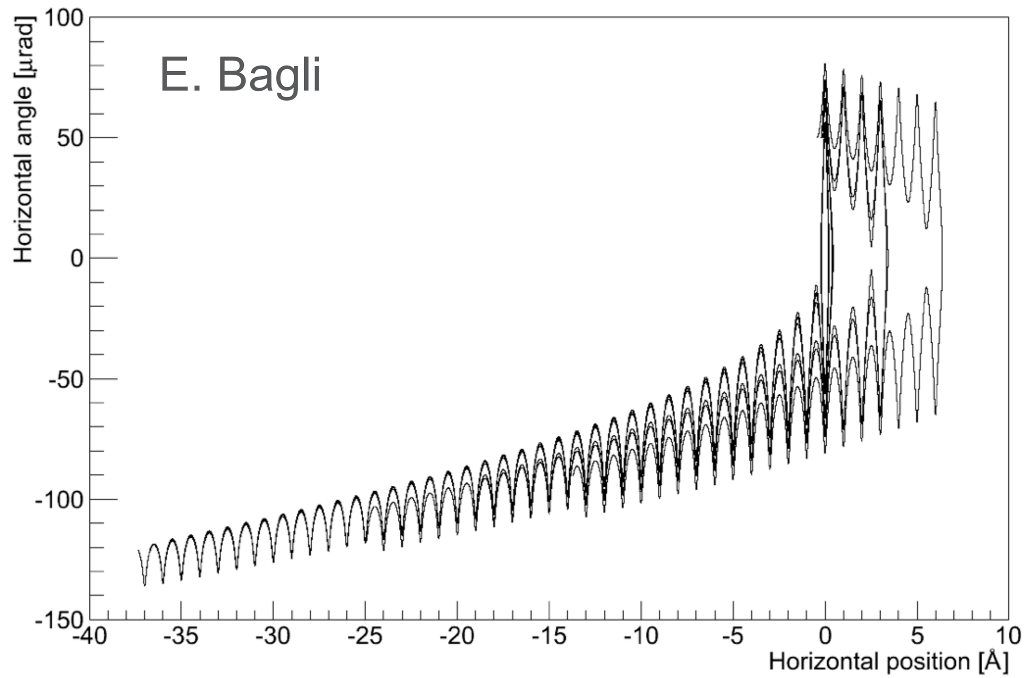
Potential shape differs depending on polarity



Phase Space (bent crystal)

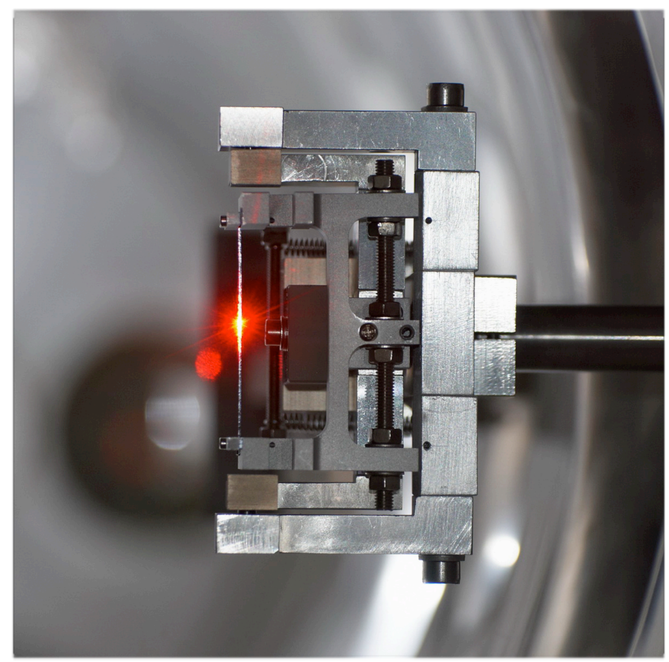
- Same topology as a (moving) rf bucket





Motivation (deflection)

- Bent crystals can deflect high energy beams with small bending radii (O(0.1m)). At 30 GeV, ≈ 1000T B-field(!)
  - 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?



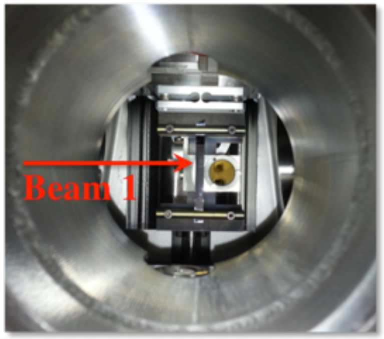
CERN SPS-UA9 collimator crystal

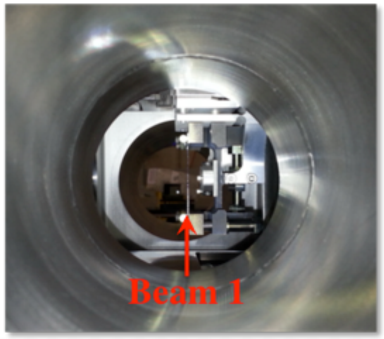
Hardware installed in the LHC

LHC Collimation Project CERN

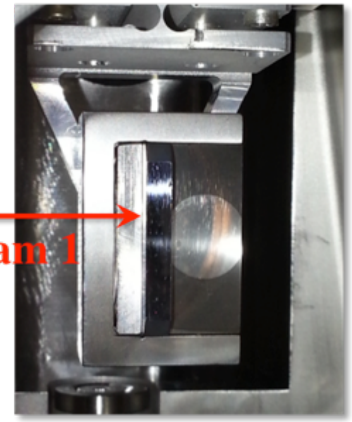
Two crystals *installed in the* ***IR7 (Beam1)*** *during* ***April 2014: (developed in the UA9 framework)***

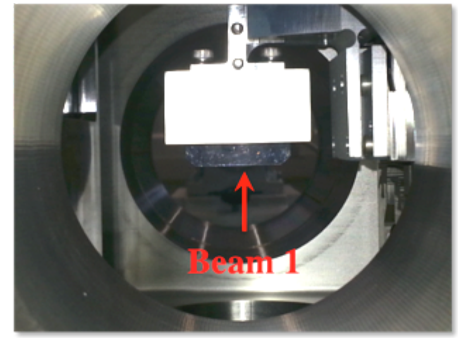
Silicon Strip crystal in the horizontal plane





D. Mirarchi, CERN

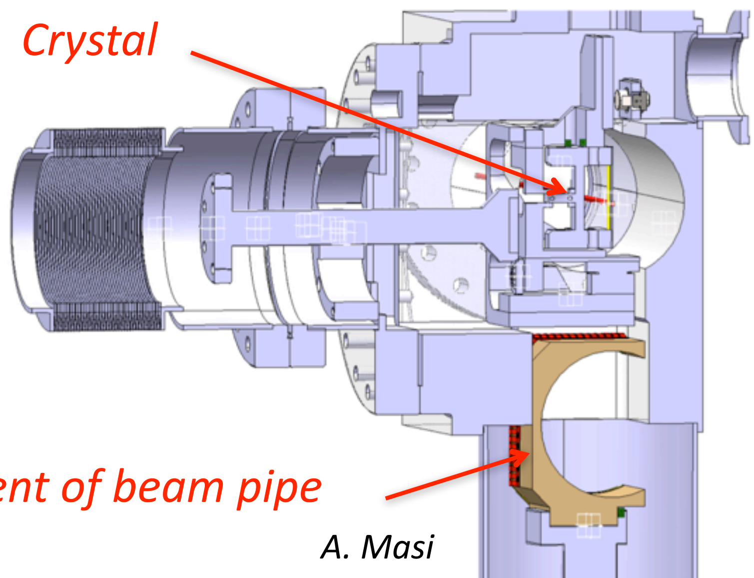




Quasi-mosaic crystal in the vertical plane

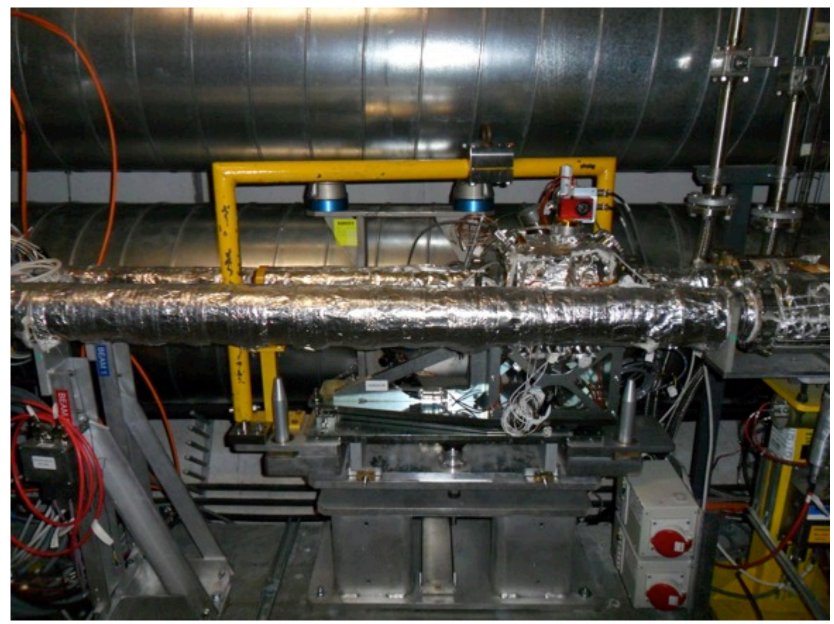
And relative goniometers: (UA9 framework)

- ✓ Piezo actuator in closed loop (angular stage)
- ✓ Transparent during normal operation



Movable segment of beam pipe

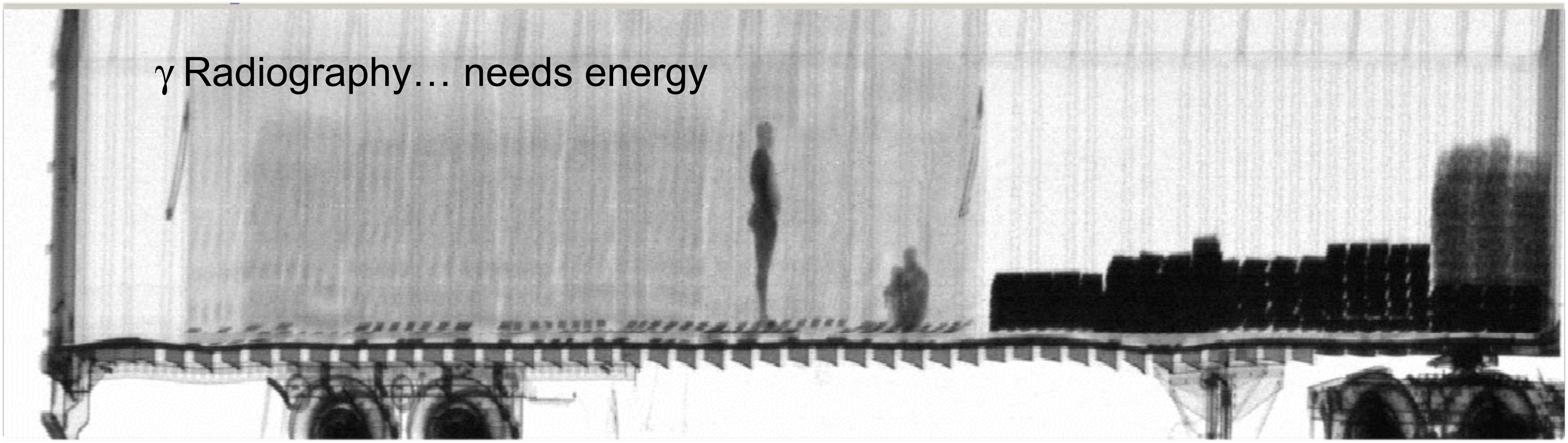
A. Masi



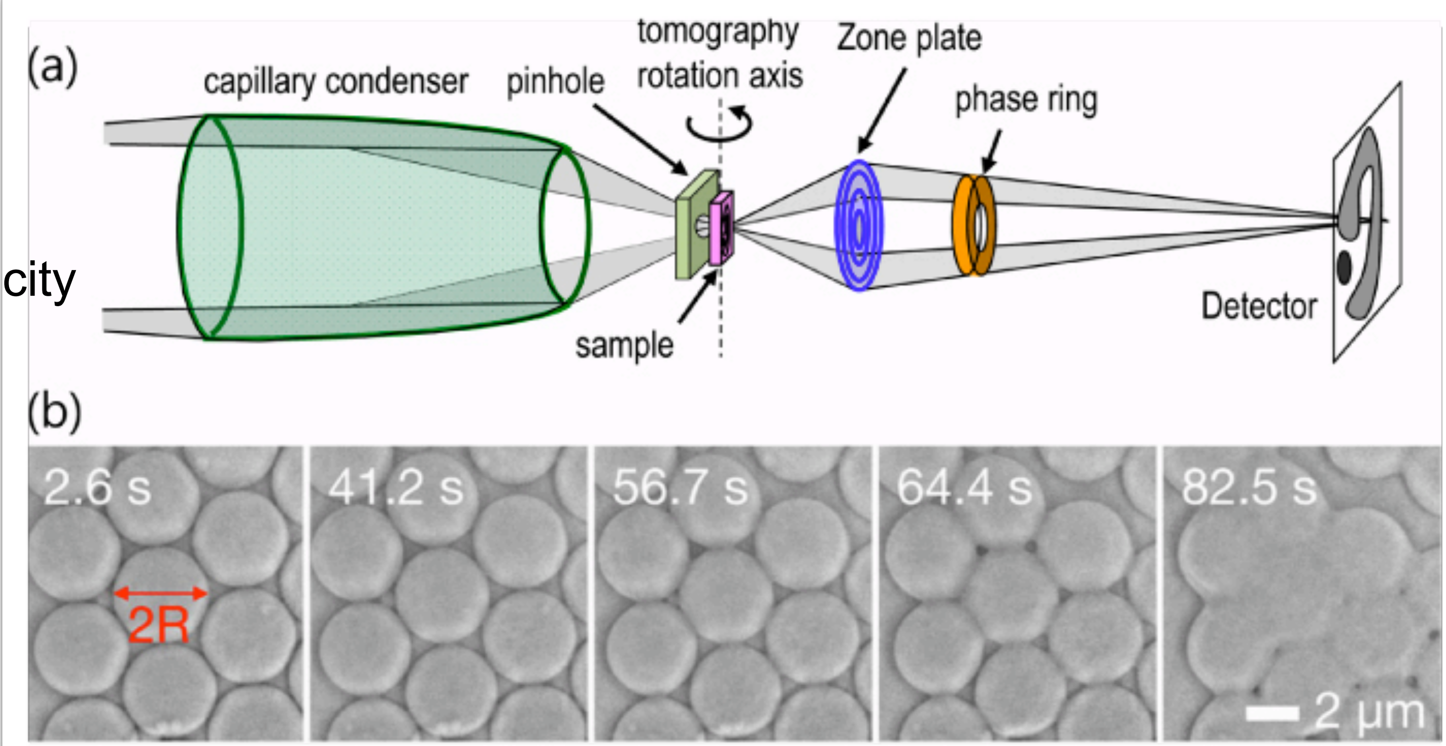
Motivation (radiation)

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

Some Potential Applications



Phase-contrast Radiography… needs monochromaticity



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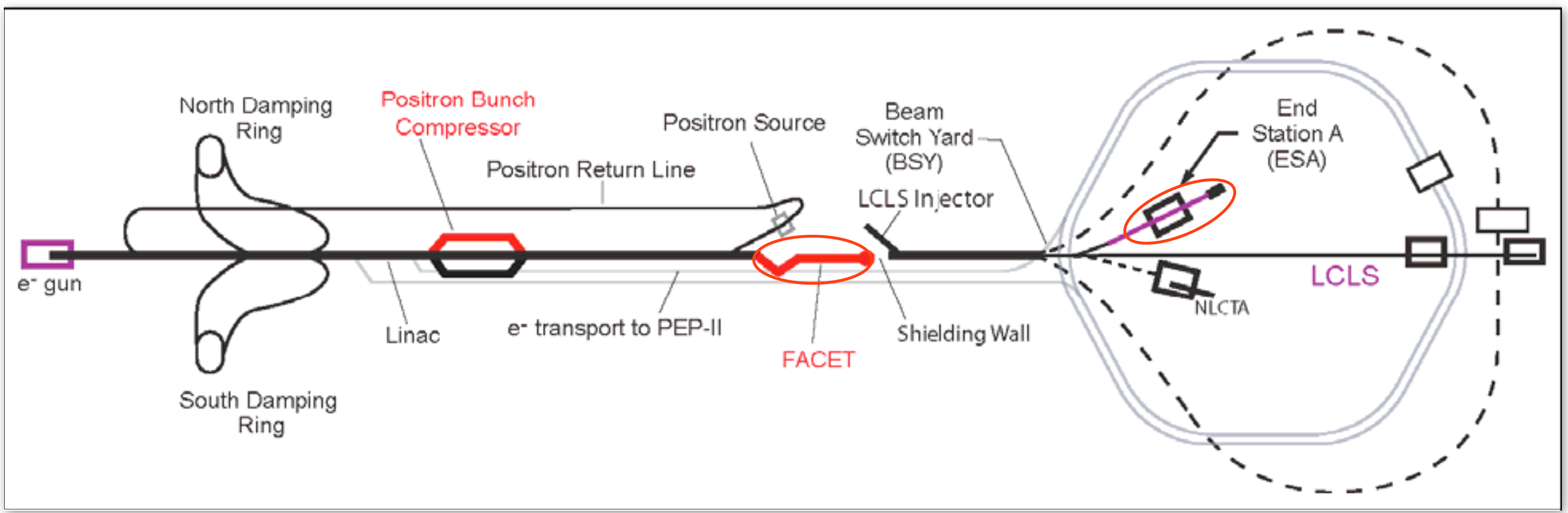
FACET and the End Station A Test Beam (ESTB)

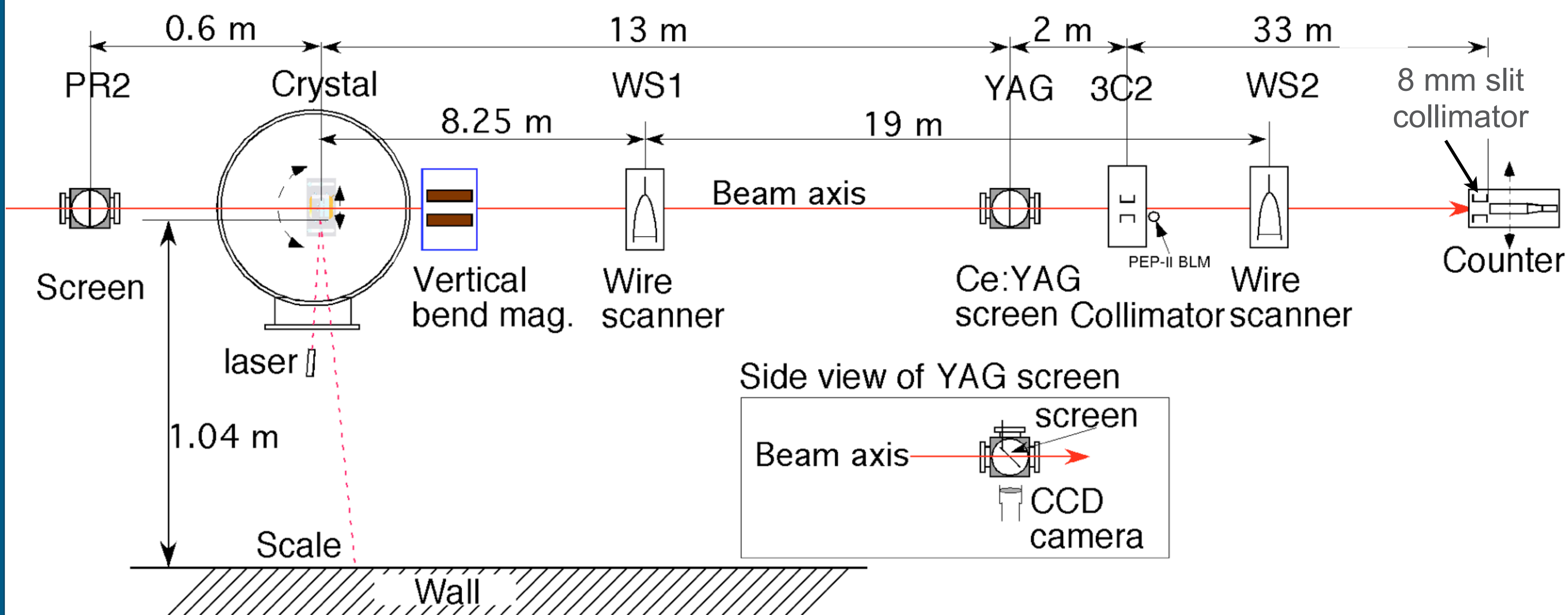
- ESTB: up to 15 GeV e^-, 5 Hz, ≤ 200 pC/pulse
  - “pulse stealing” from LCLS
- FACET: 20 GeV e^+ or e^-, 2 nC/pulse, 10 Hz, “20^3 μm^3”
- control of optics, momentum spread
  - both can provide relatively parallel beam (<10 μrad)
  - FACET has a e^- spectrometer downstream; ≈ 0.1% resolution



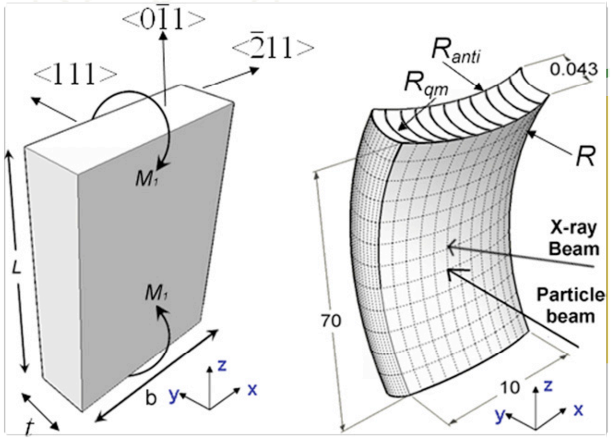
T513/T523 Experiment Layout (ESTB)

Top View, not to scale

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



Main crystal features



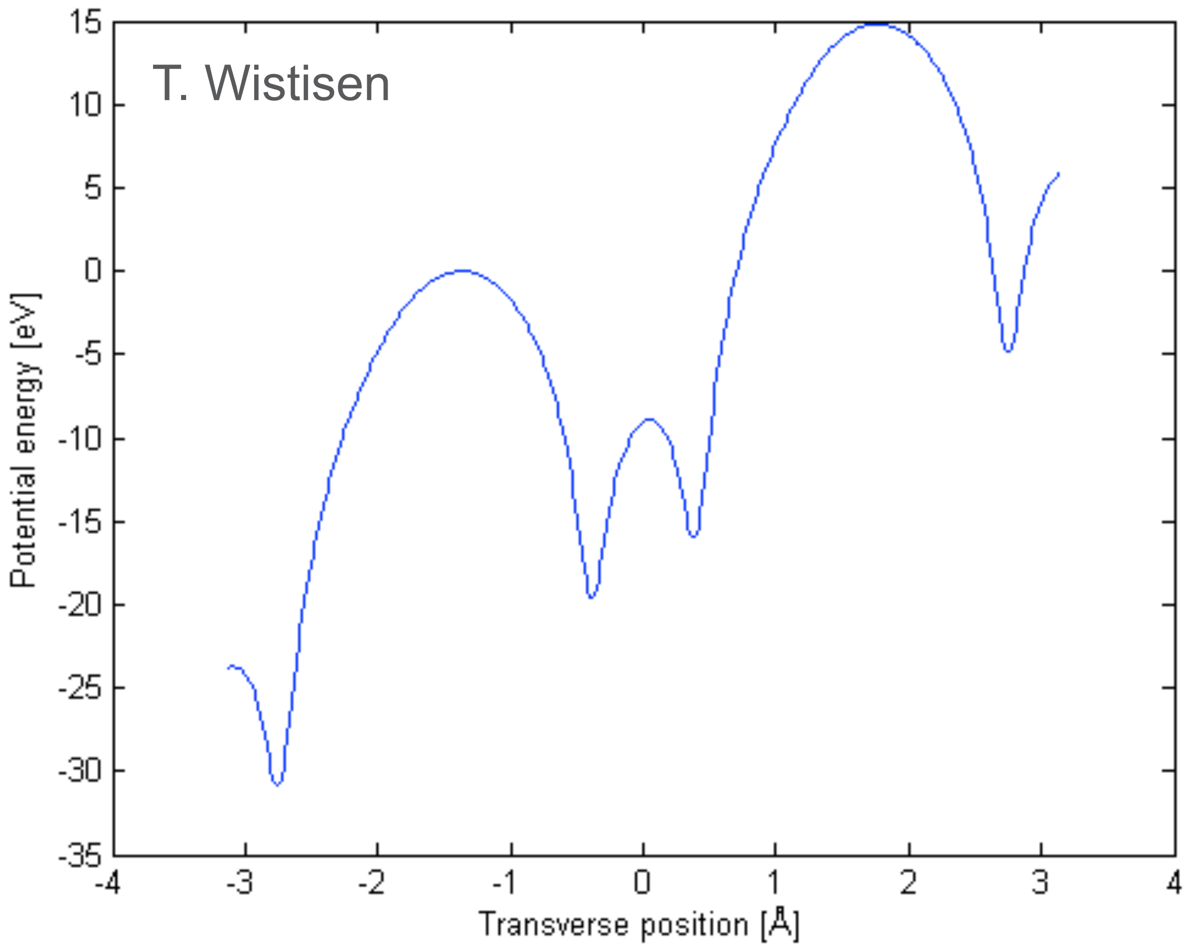
- **Crystal thickness 60±1 μm**
  Once the crystal will be back in Ferrara we will measure crystal thickness with accuracy of a few nm.

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

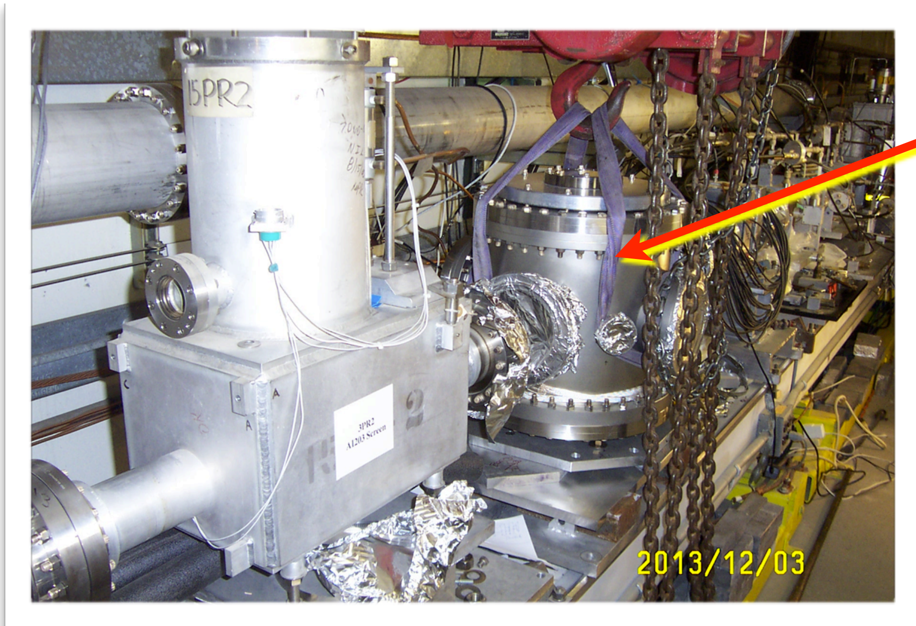
- **Bending angle 402±9 μrad (x-ray measured). If needed I can provide a value with lower uncertainty.**

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

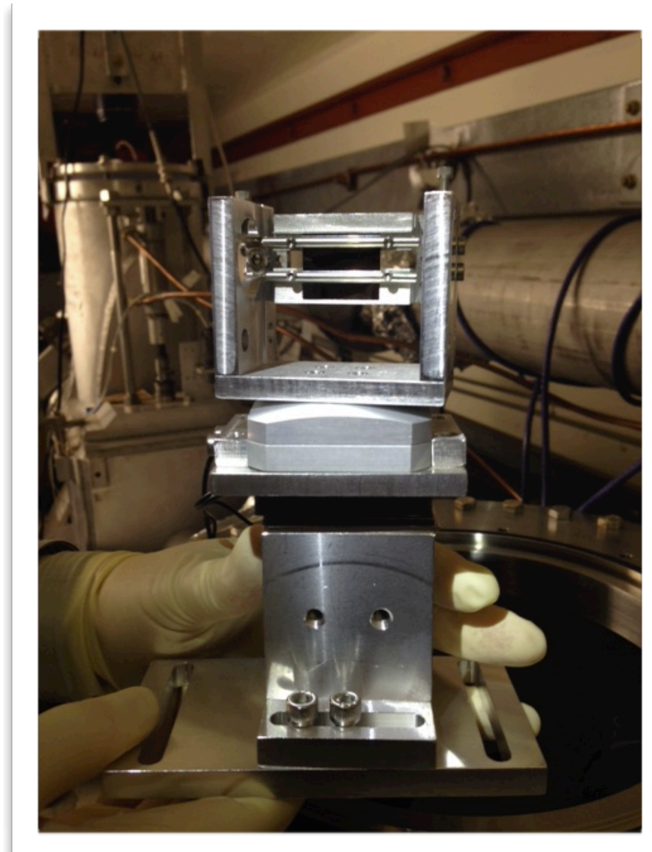
$\theta_{crit} = \sqrt{2U_0/E} \approx 80\ \mu\mathrm{r}$ @ 6.3 GeV



T-513 being installed (by ESTB Group)

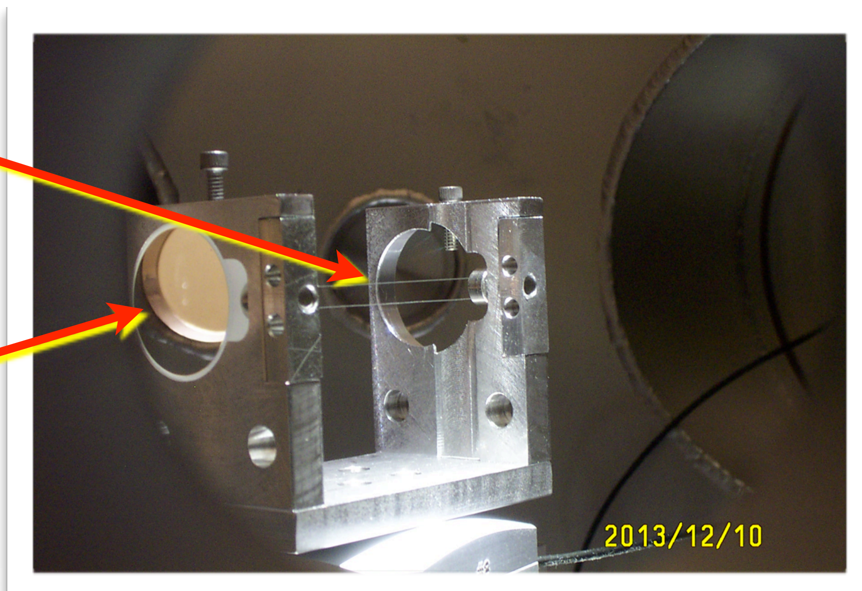


Chamber
(“Kraken”)



Beam finder wire installed for 1st beam

Mirror for angle readout



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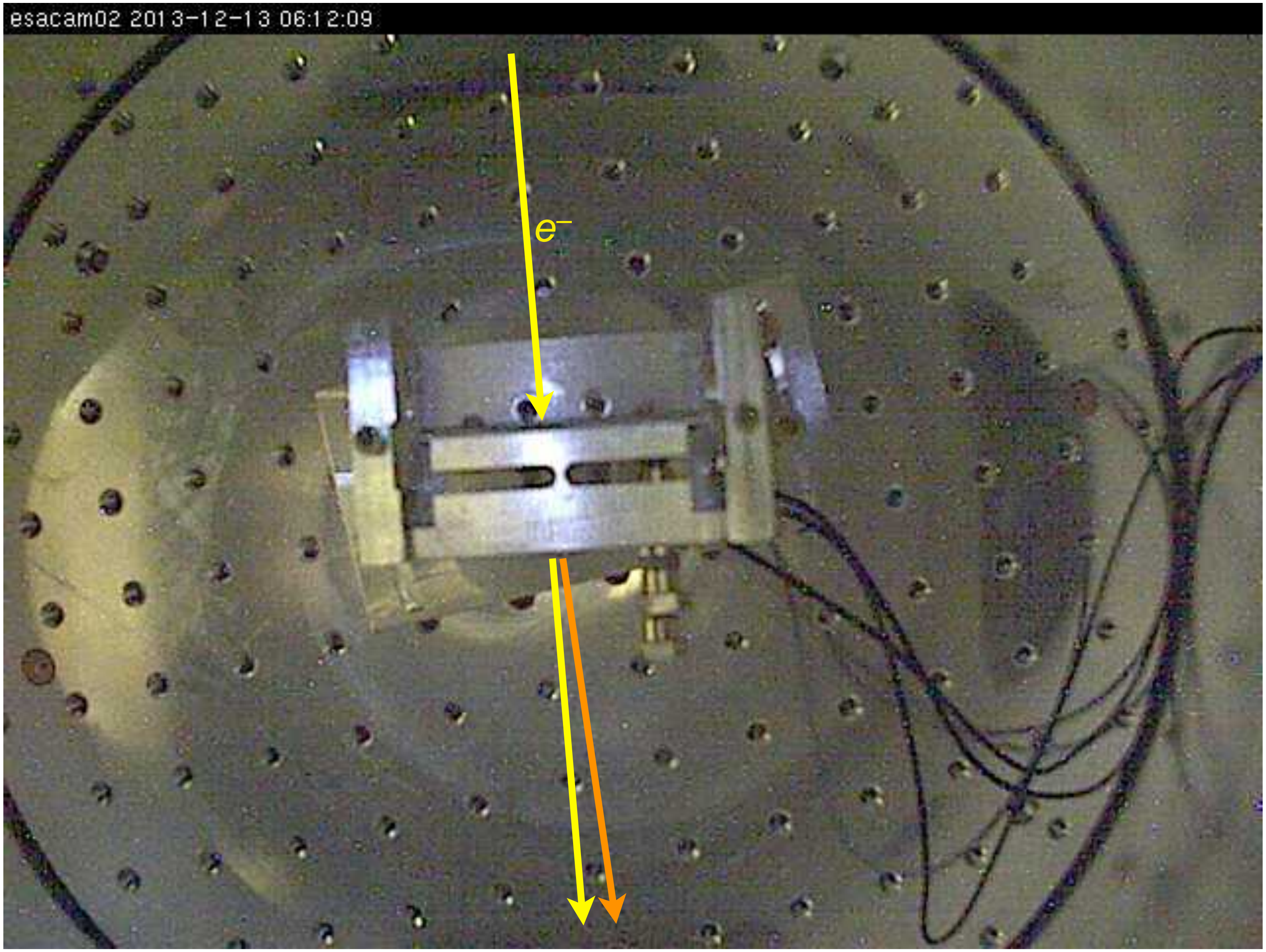
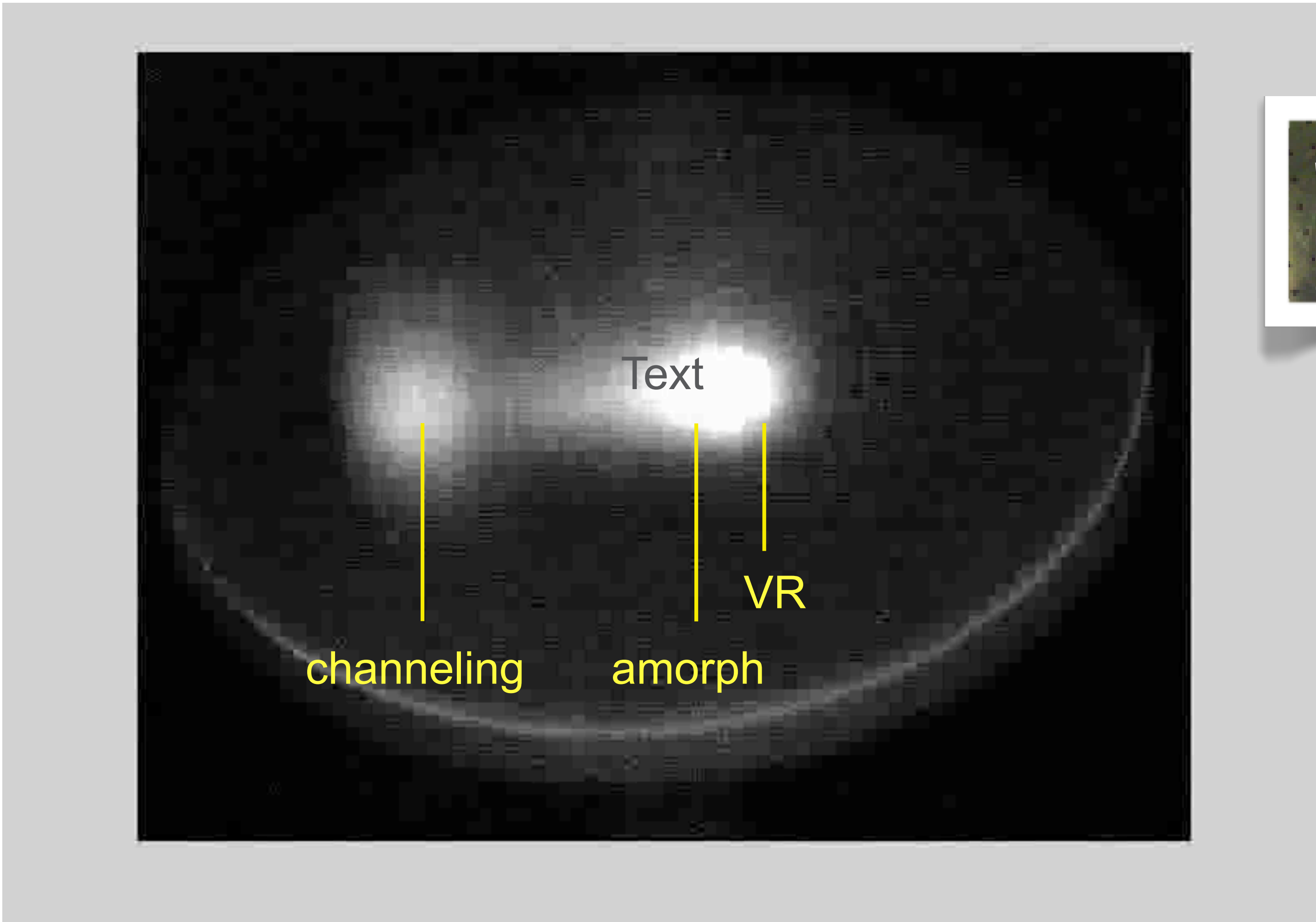
Crystal mounted in "Kraken" Chamber in ESA

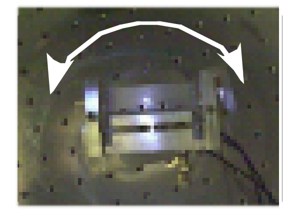


Crystal-Rotation @ 4.2 GeV

https://www.sciencedaily.com/releases/2015/02/150225132110.htm

(Movie credit: T. Wistisen)

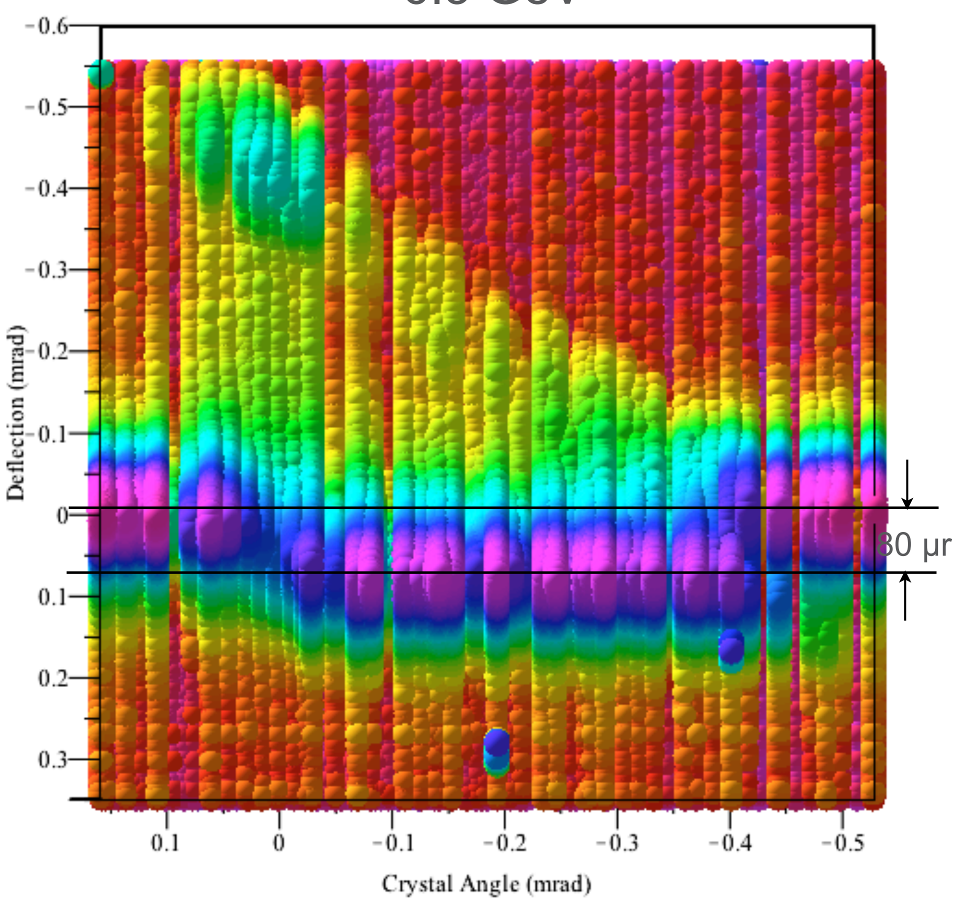




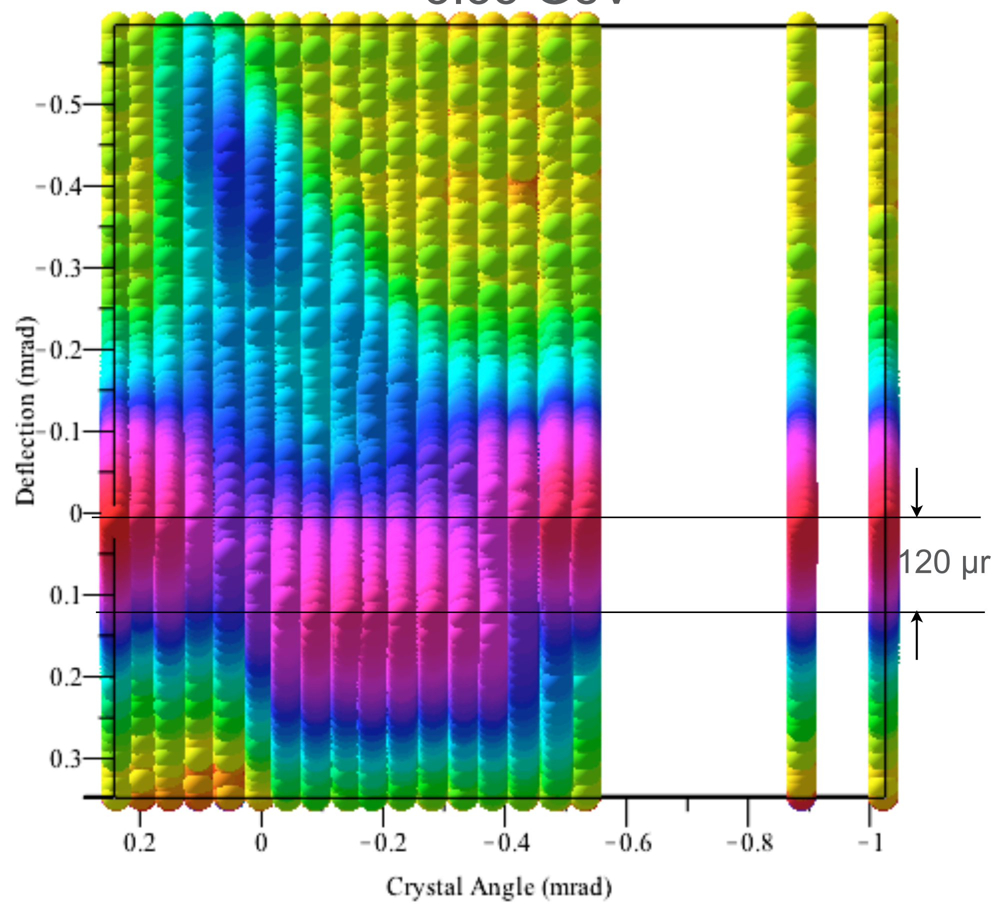
Triangle Plots

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

6.3 GeV

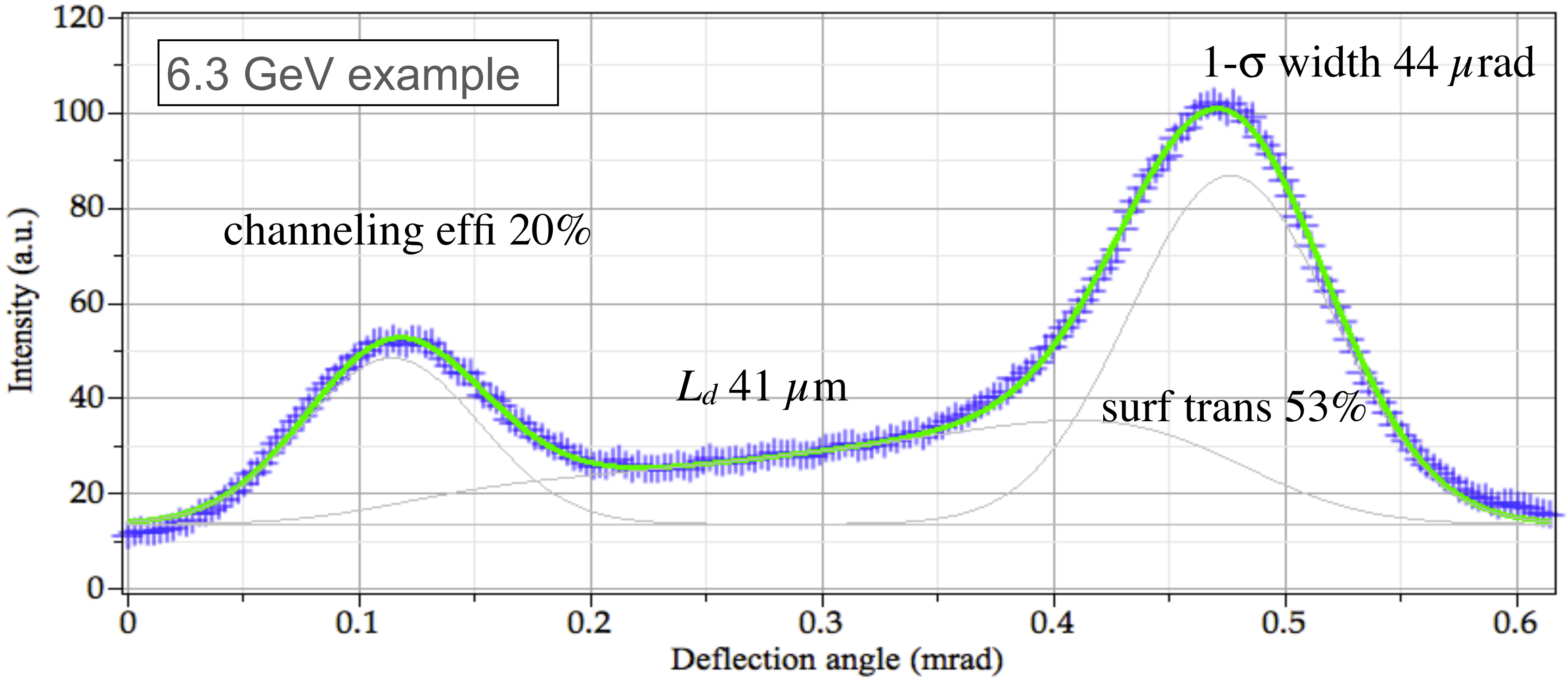


3.35 GeV



Fit to Intensity Distribution

- unfold 2 peaks + exponential dechanneling tail

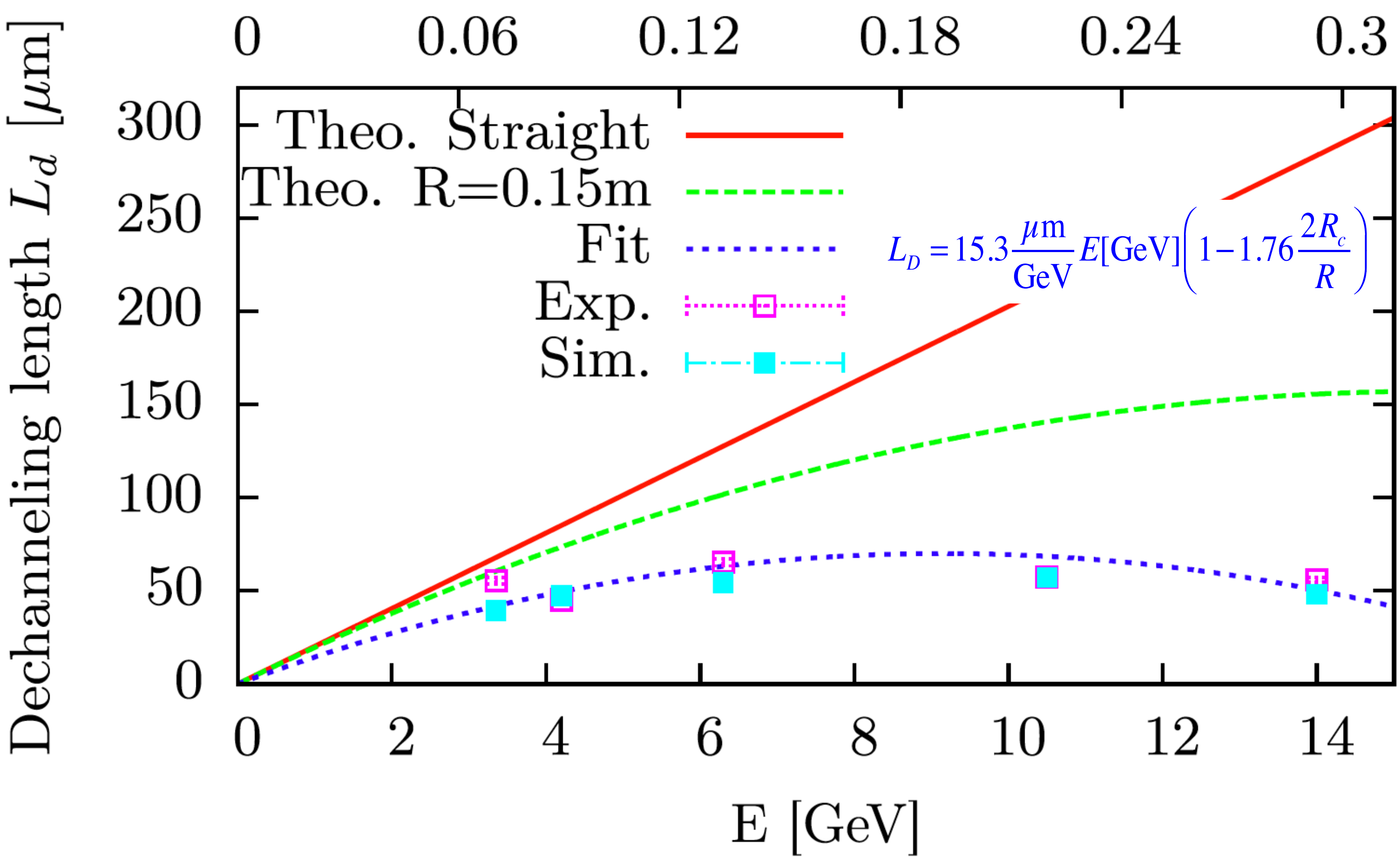


$$\frac{dP}{d\theta}(\theta) = \frac{1-P_1}{2\theta_d} e^{\frac{\sigma_2^2}{2\theta_d^2}+\frac{\mu_1}{\theta_d}-\frac{\theta}{\theta_d}} \left(\mathrm{erf}\left(\frac{\mu_2-\Delta\theta}{\sqrt{2}\sigma_2}\right) - \mathrm{erf}\left(\frac{\mu_1-\Delta\theta}{\sqrt{2}\sigma_2}\right)\right)$$

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

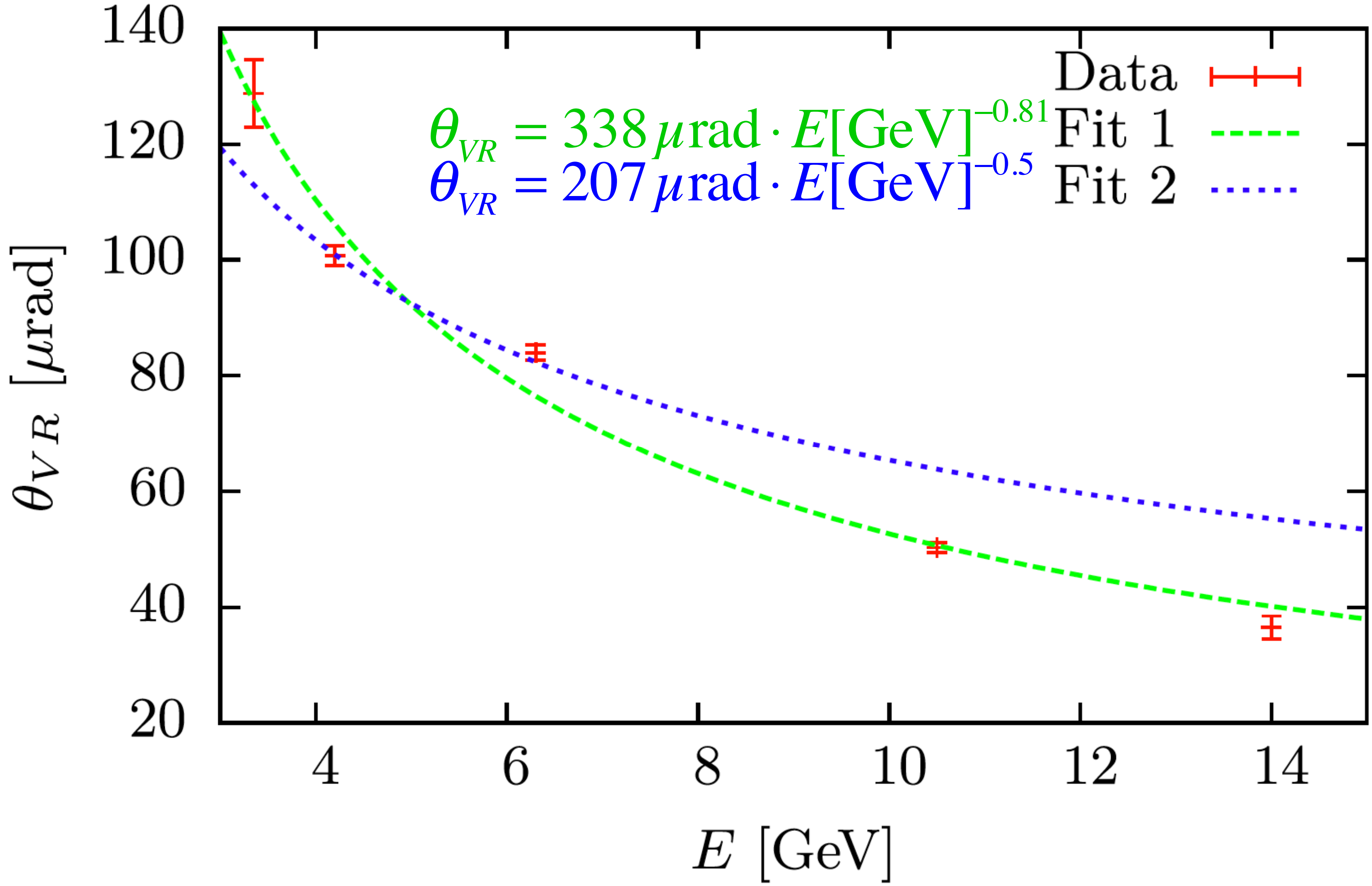
Dechanneling Length of e^-

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



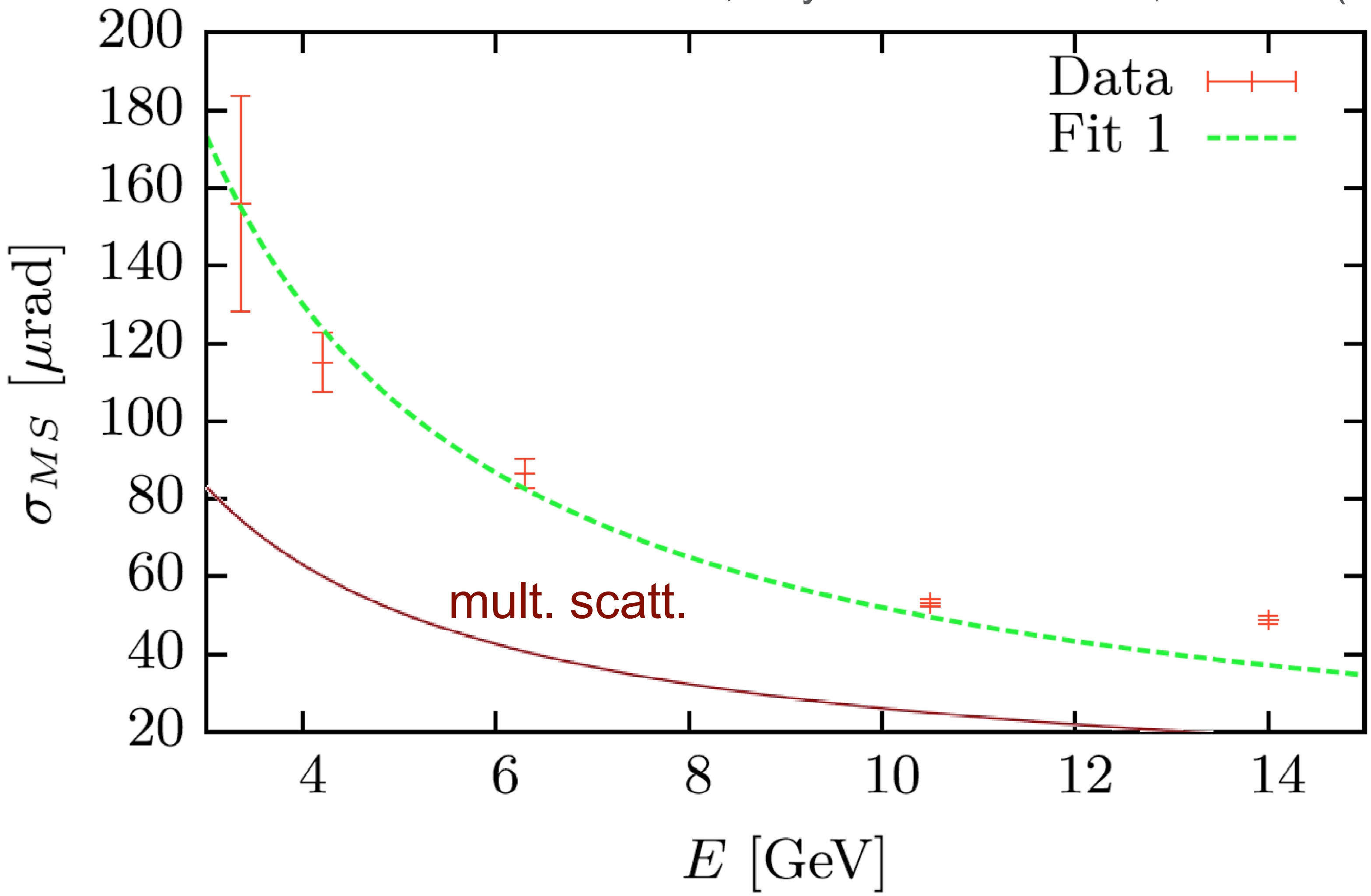
Volume Reflection Angle

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



Scattering in "Free" Direction

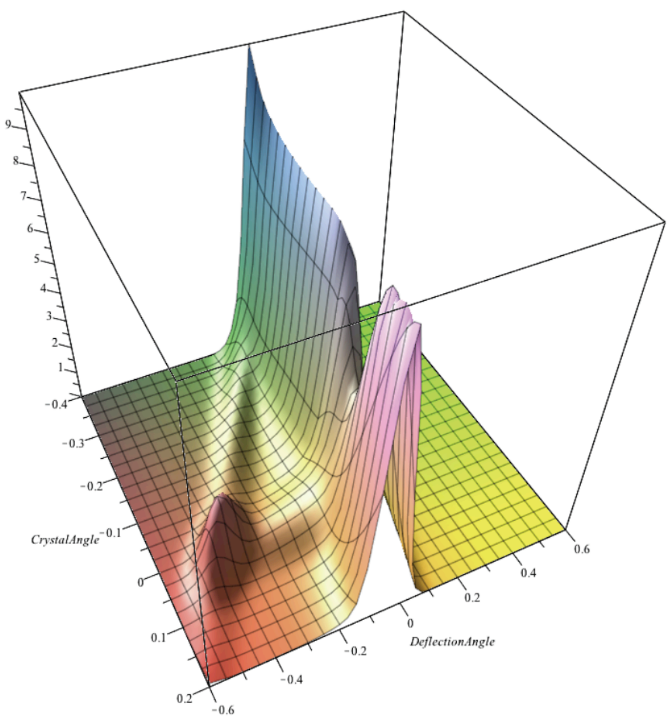
T.N. Wistisen *et al.*, Phys. Rev. ST-AB 19, 071001 (2016)

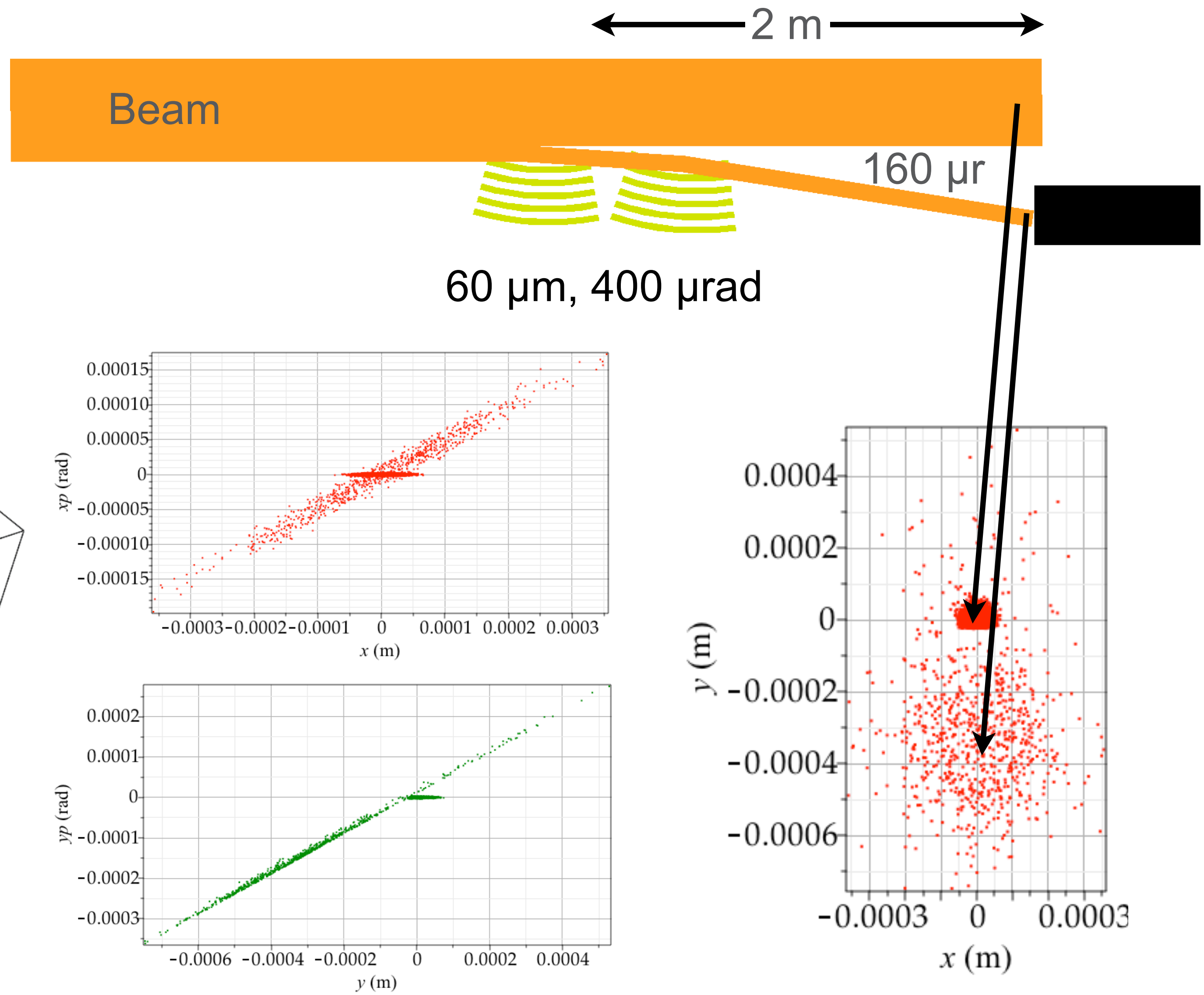


VR Collimator Concept

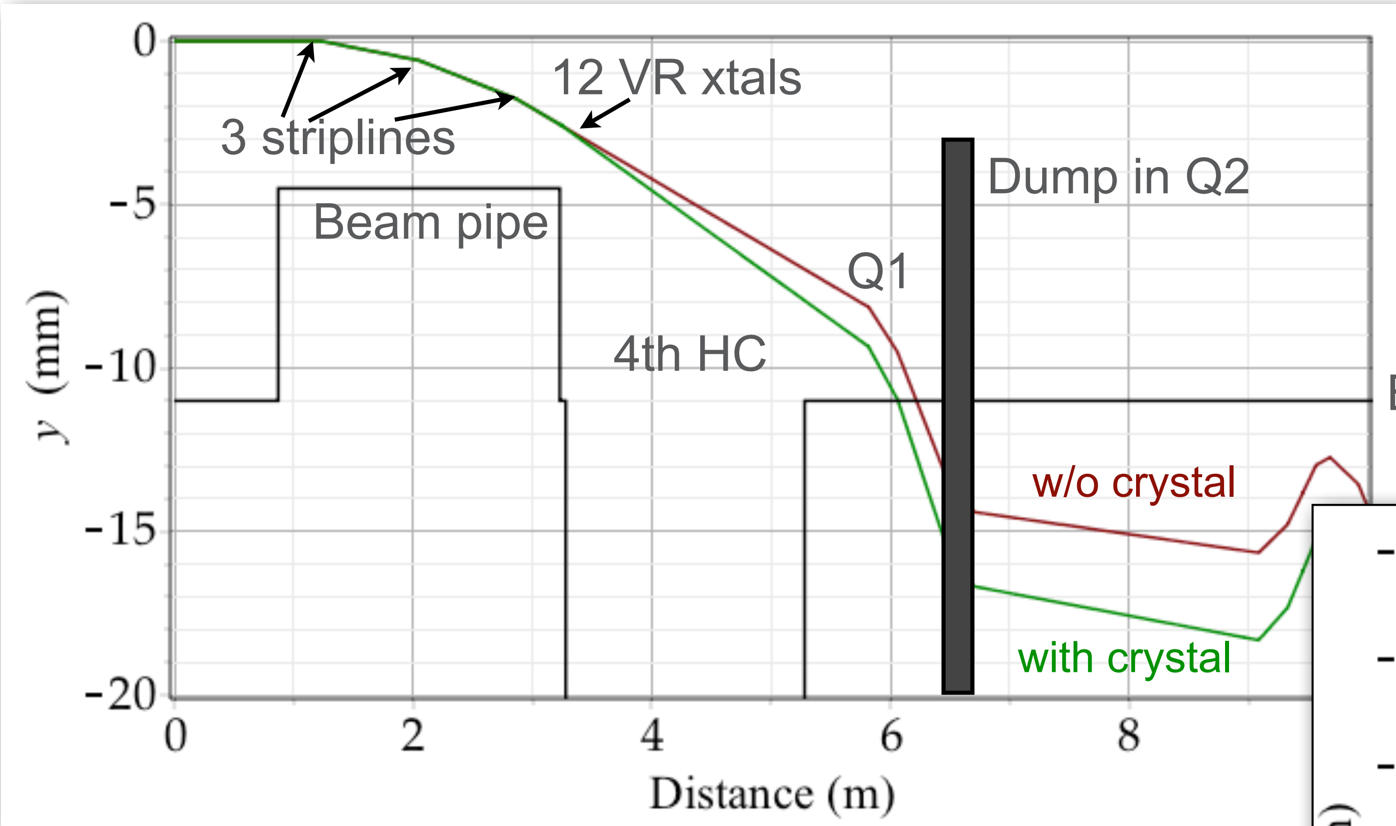
- The T513 data can be used to investigate beam collimation:

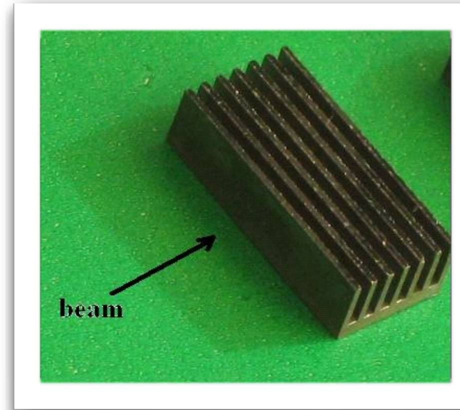
pdf to generate deflections





VR-Deflector assisted swap-out dump

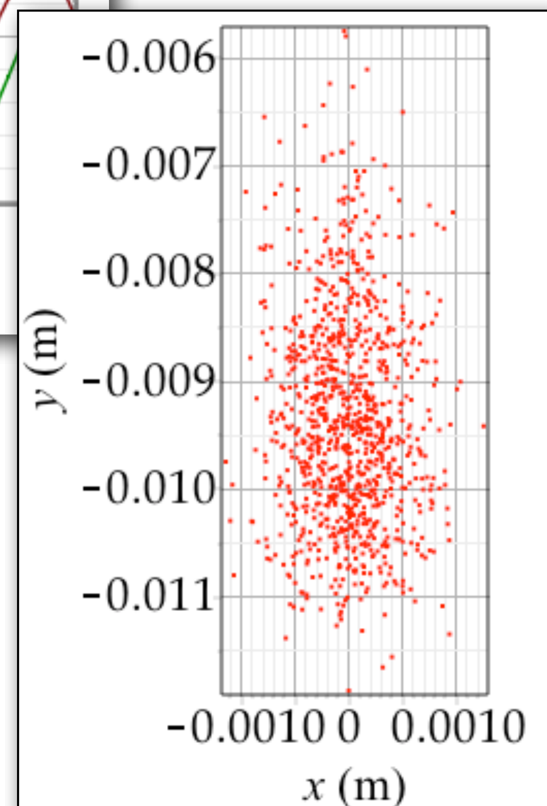




12 T-513 Crystals in VR orientation
(not optimal)
they nominally add ≈ 1 mrad;
about half that in this toy-model

In practice would need ^{12}C crystals

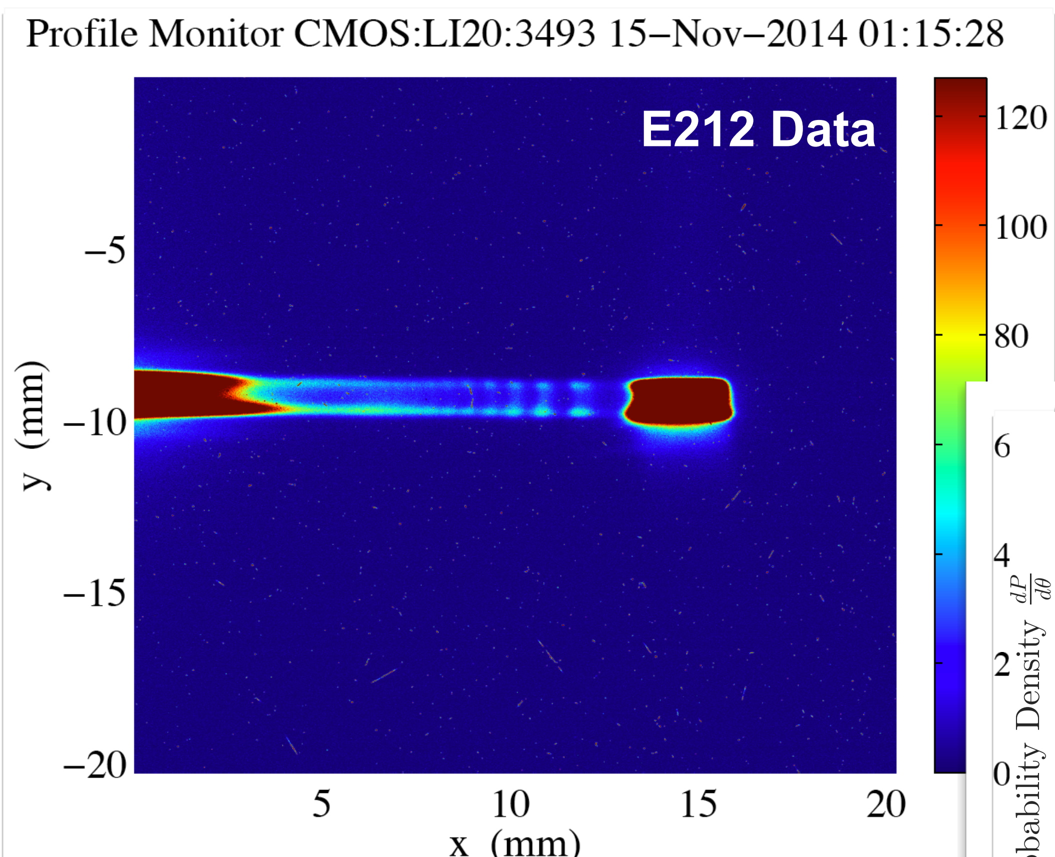
scatter and deflect



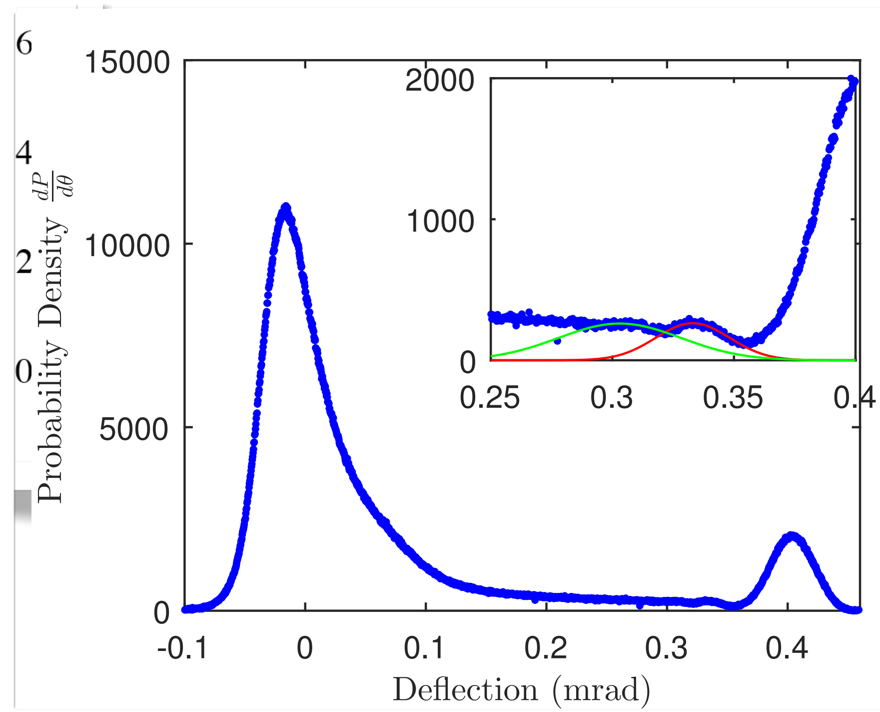
E212: First Channeling Data of 20 GeV e^+ in Bent Crystal

- Raw data

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

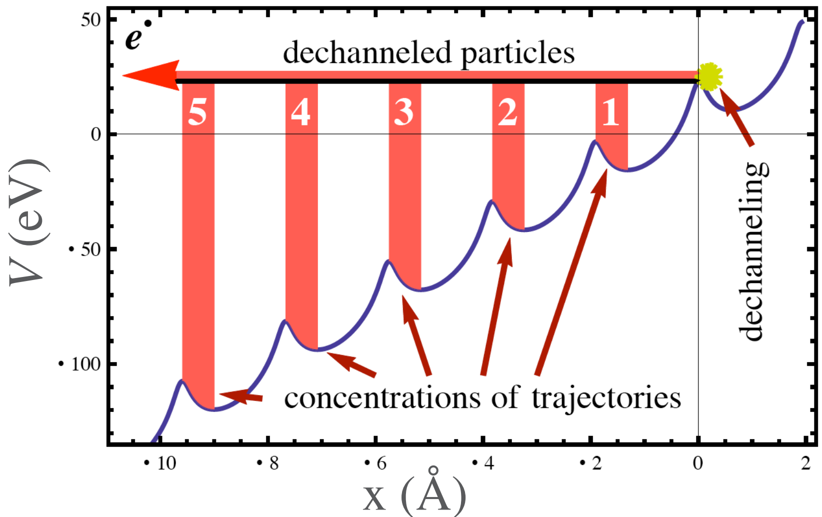


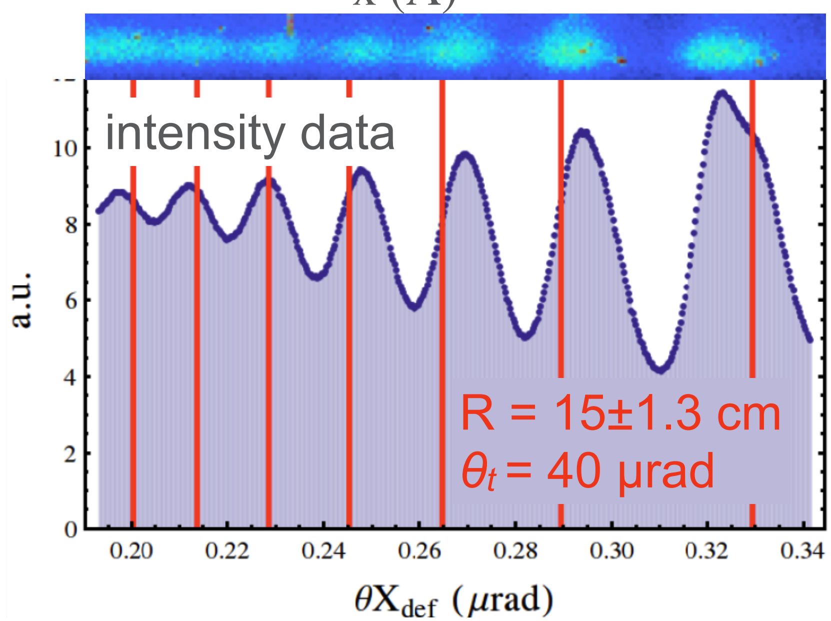
e^- data, 20.35 GeV, 10^{10} e^-/pulse



Analysis of the "Quasi-Channeling Oscillations"

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

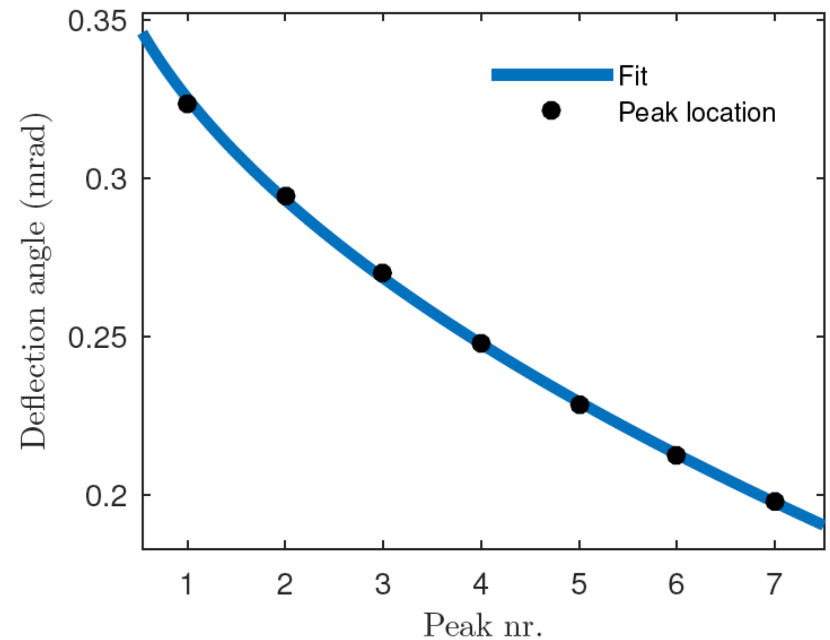




T. Wistisen *et al.*, subm. to PRL

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

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



Summary of Deflection Results

- Channeling efficiency ≈ 18…24 %, VR up to 95%
- Dechanneling length ≈ 40…60 µm
  - little dependence on the beam energy in our range (3.35…14 GeV)
- 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 –> $X_0/4$)
- Quasi-Channeling oscillations observed with e^+ (and hints with e^-).

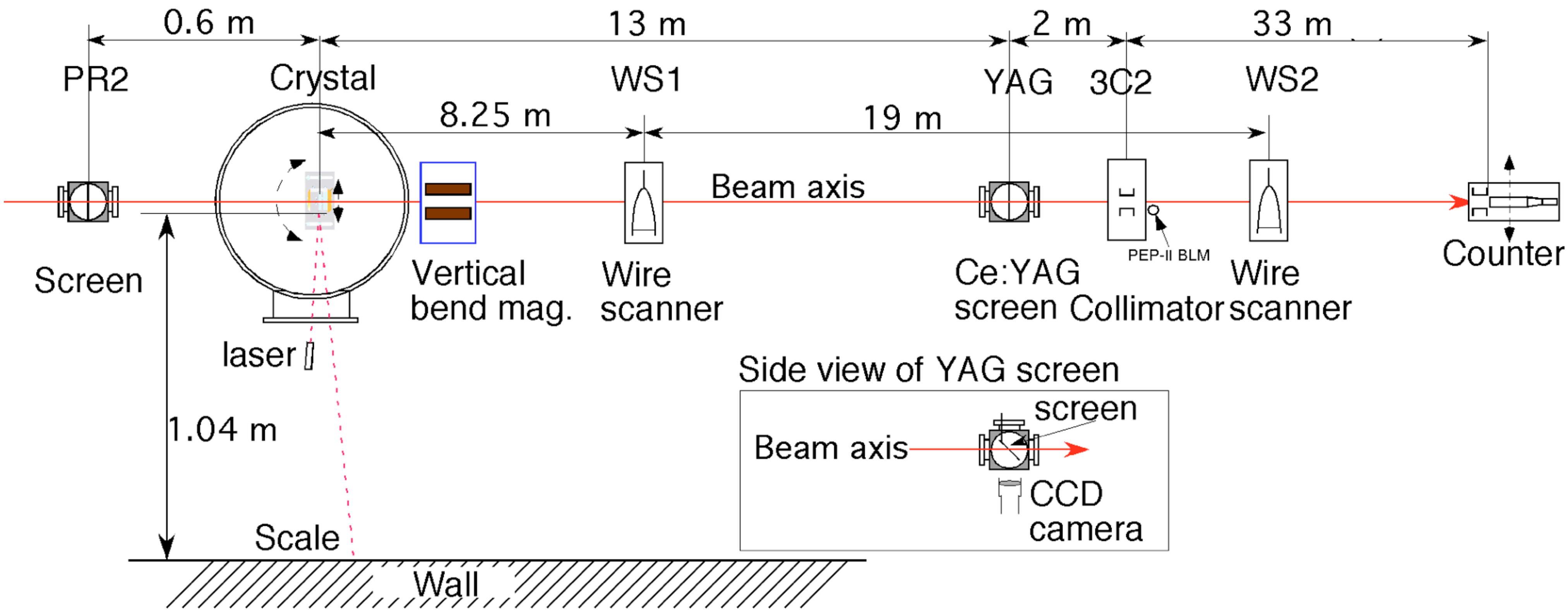
Gamma-Ray Experiment (T523)

- 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

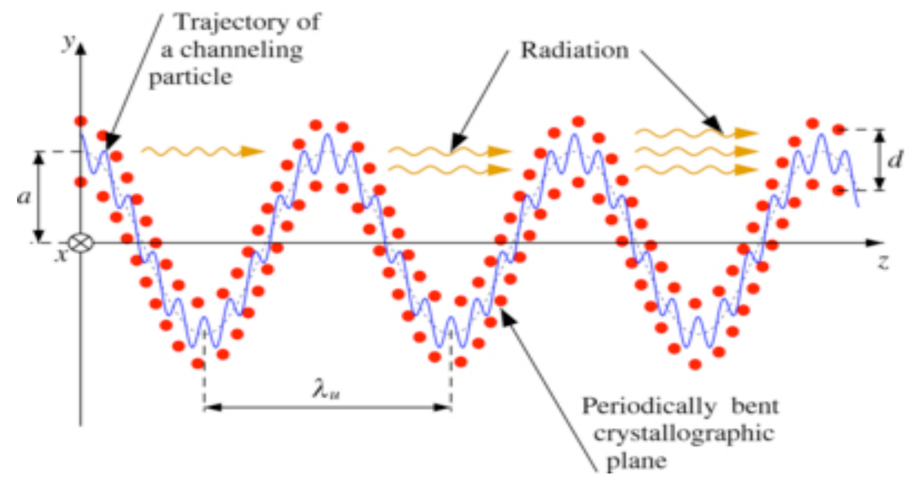
T513/T523 Experiment Layout (ESTB)

Top View, not to scale



Monolithic Undulator

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



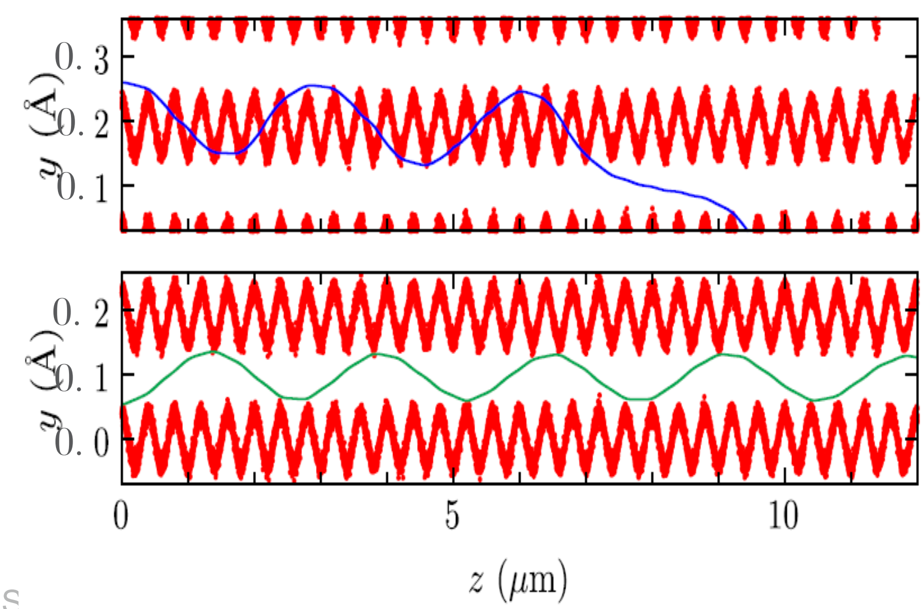
Small amplitude,
short period (SASP, Kostyuk 2014):

"Slow" betatron oscillations,

fast undulations

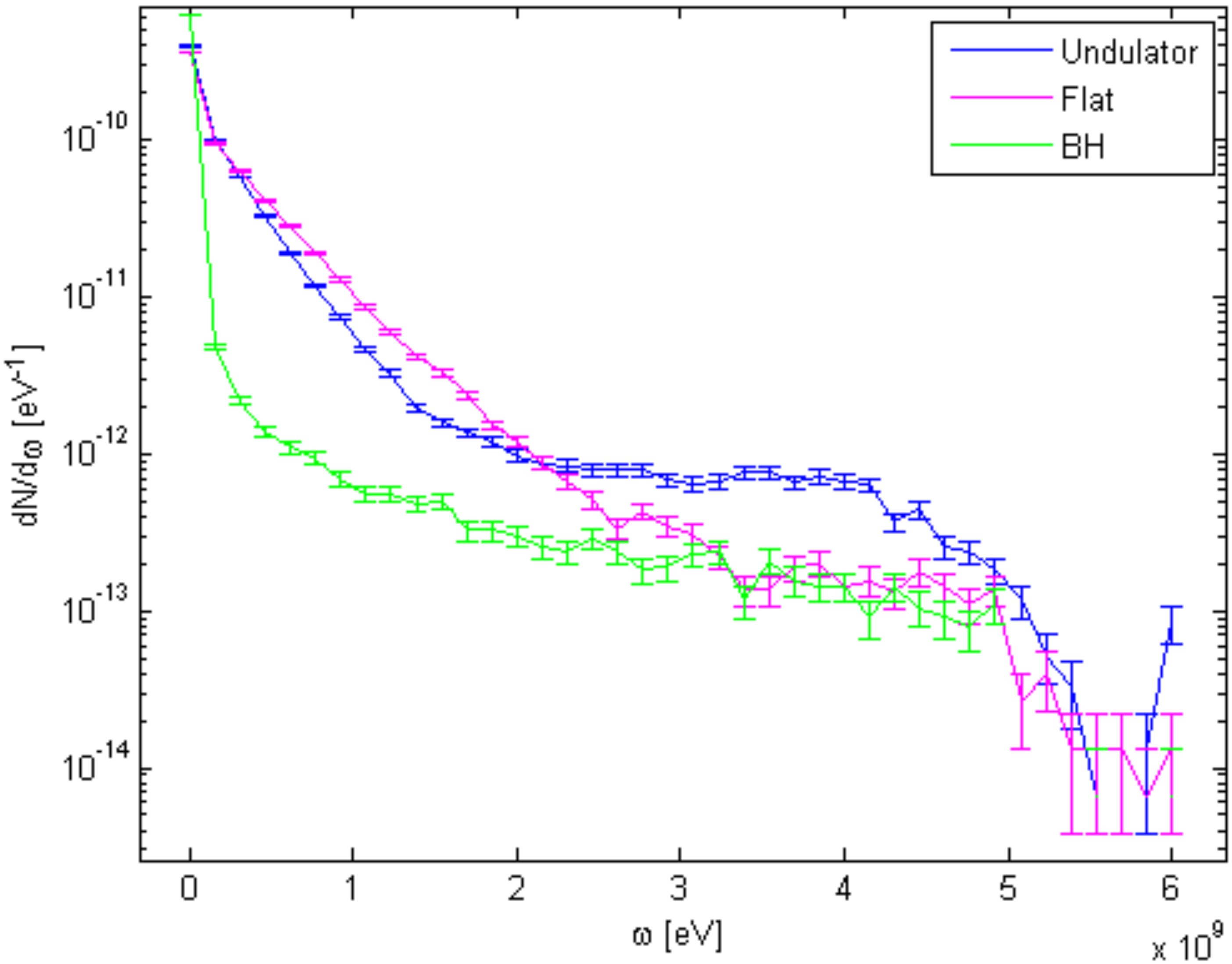
- 37 µm long, 120 periods, (110)
- 0.7 GeV @ 6.2 GeV e^-
- 4 GeV@ 16.1 GeV e^-
- K ≈ 0.07

$Si_{1-x}Ge_x$-graded composition



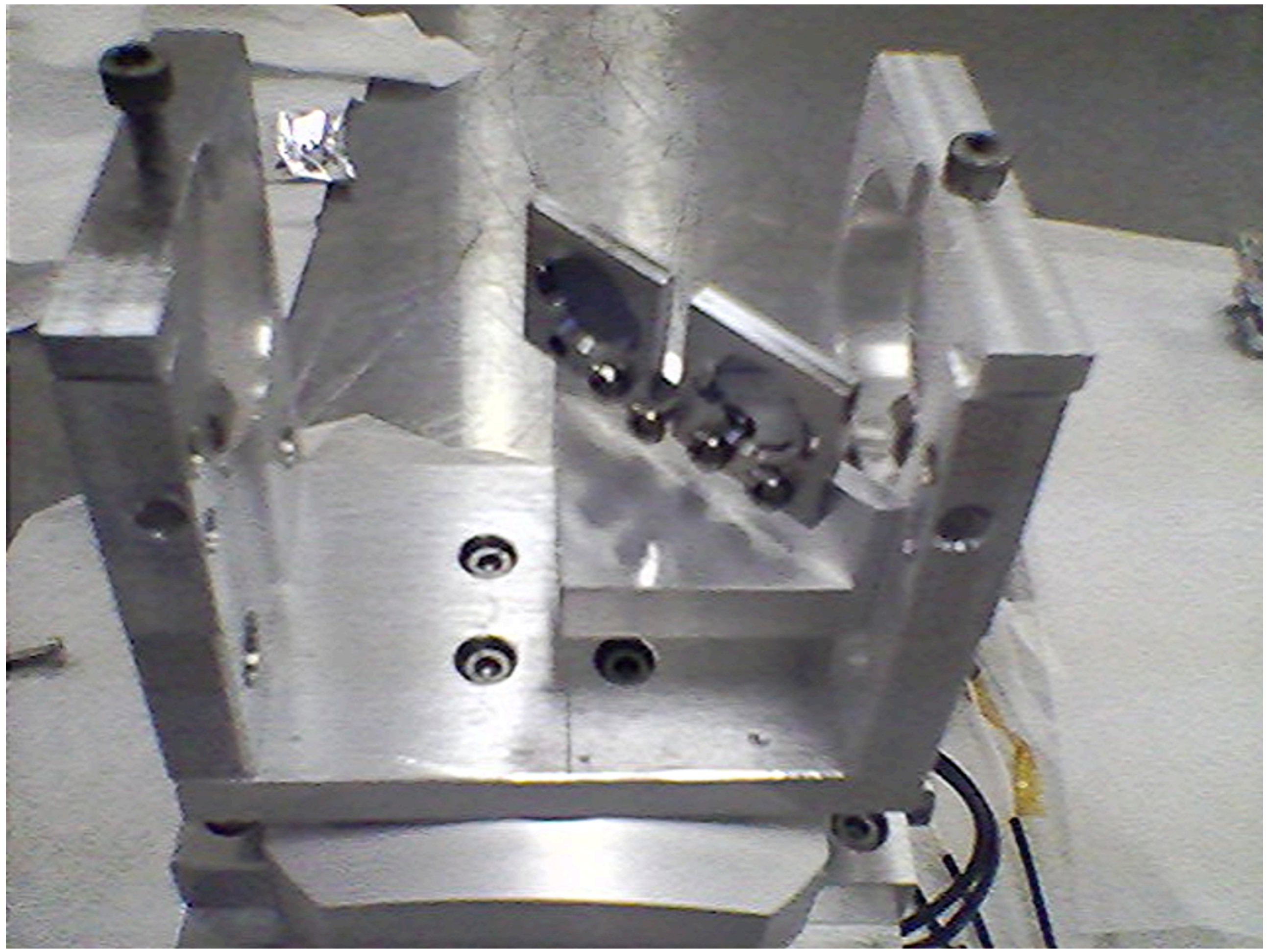
Expected spectra, 16 GeV

Note: Spectral feature mostly from over-the-barrier motion as $R_{wigg} < R_c$

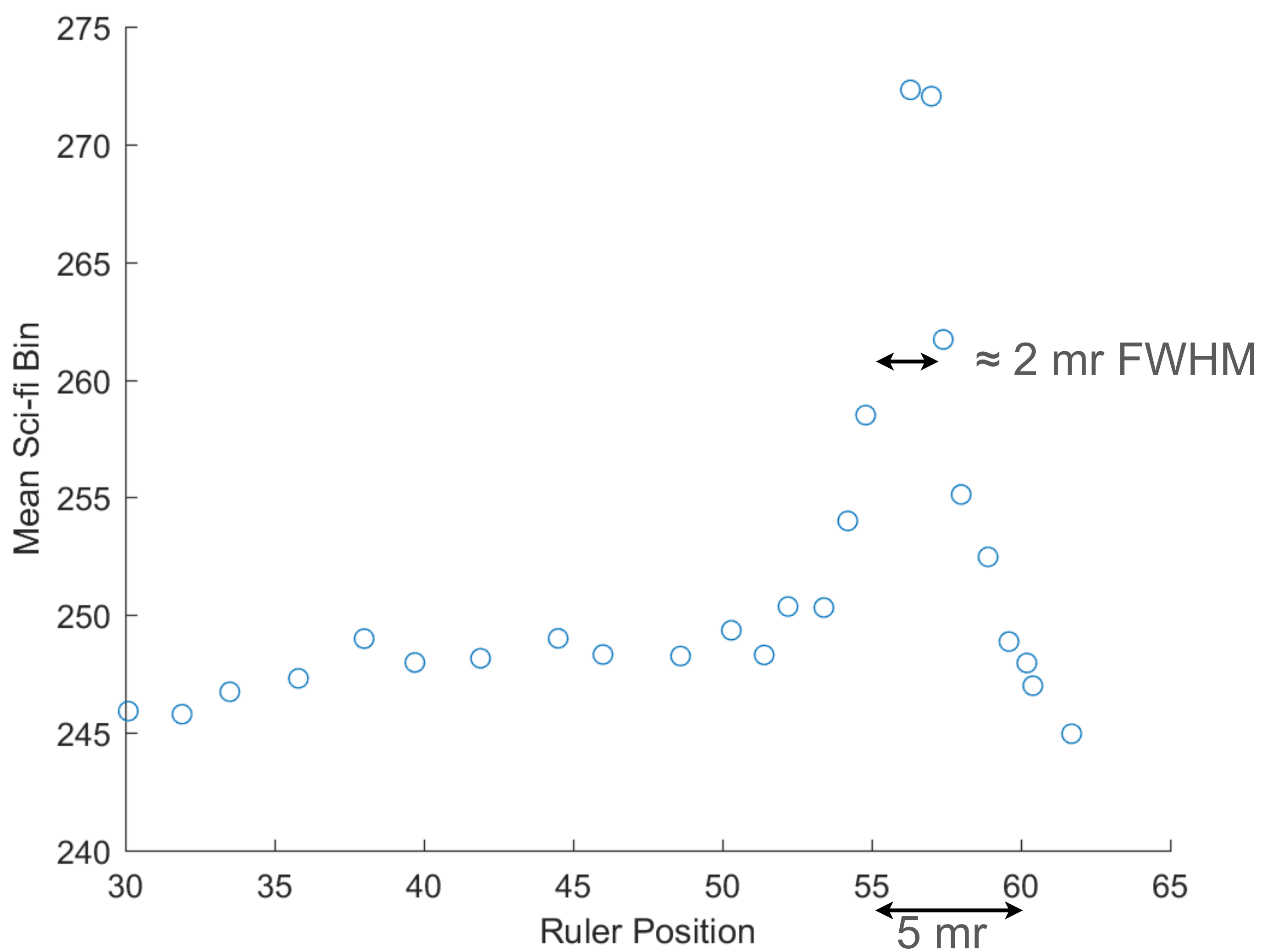


Aarhus Monolithic Undulator

- 37 µm thick; 120 periods.

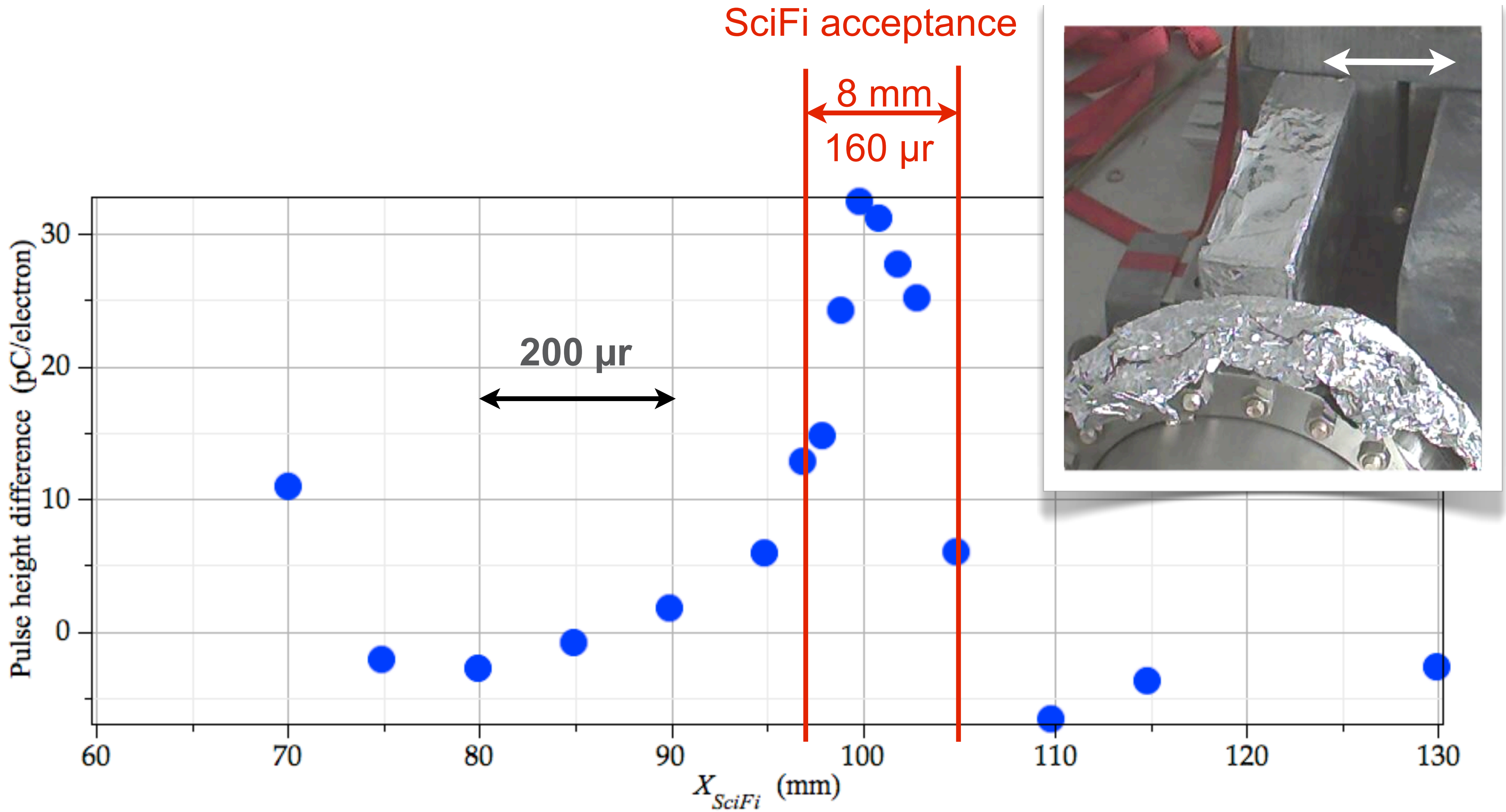


Crystal Alignment with Full Beam



Angular Distribution Aligned – Amorph

U. Wienands *et al.*, NIM-B (2017) (in press)

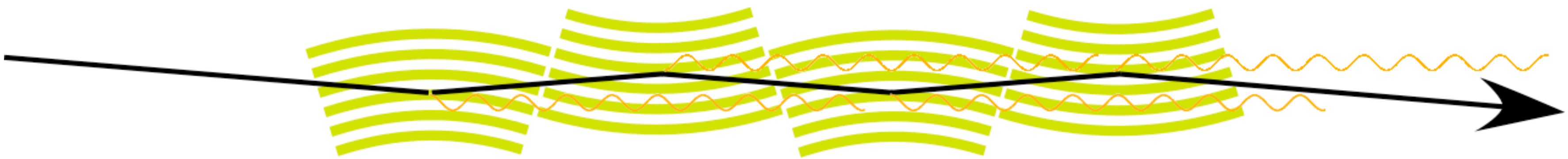


E212/T523 Summary

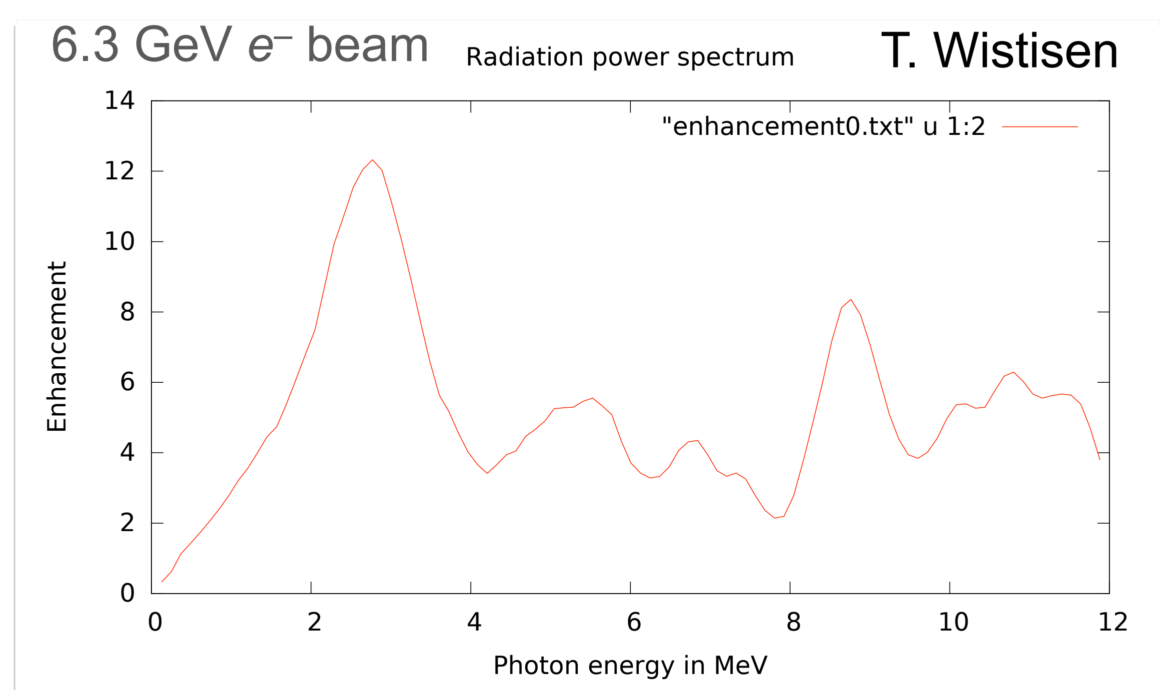
- Gamma rays detected from the crystals
  - In 2015 we saw evidence for channeling and VR gamma rays from the Ferrara bent Crystal (60 μm, 400 μrad, 0.15 m)
  - Gamma rays from 37-μm Aarhus Undulator seen this summer
- Clearest signals in intensity distributions
  - VR radiation from Ferrara crystal
  - Channeling radiation from Aarhus undulator
  - Signal/background ratio 1:1 -> 1:4
- Energy spectra have been difficult to acquire.

VR Undulator

- Stack of bent crystals; T513-crystal-like

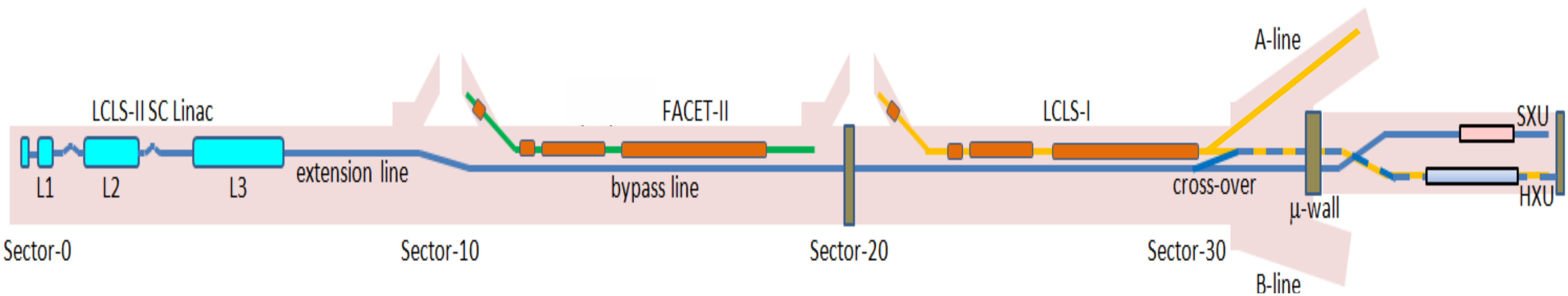


- Acceptance: θ_b–θ_{crit}
  - ≈ 300 μrad for T513 xtal
- MS: 30 μrad @ 10 GeV
  - 10 periods: 135 μrad, < 300 μrad
- A 10 period undulator could work!



Beyond T523 and E212

- 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 interest from NIU to collaborate.



Thank you!

High-Intensity spectra (cont’d)

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

Volume Reflection | empty (no crystal)