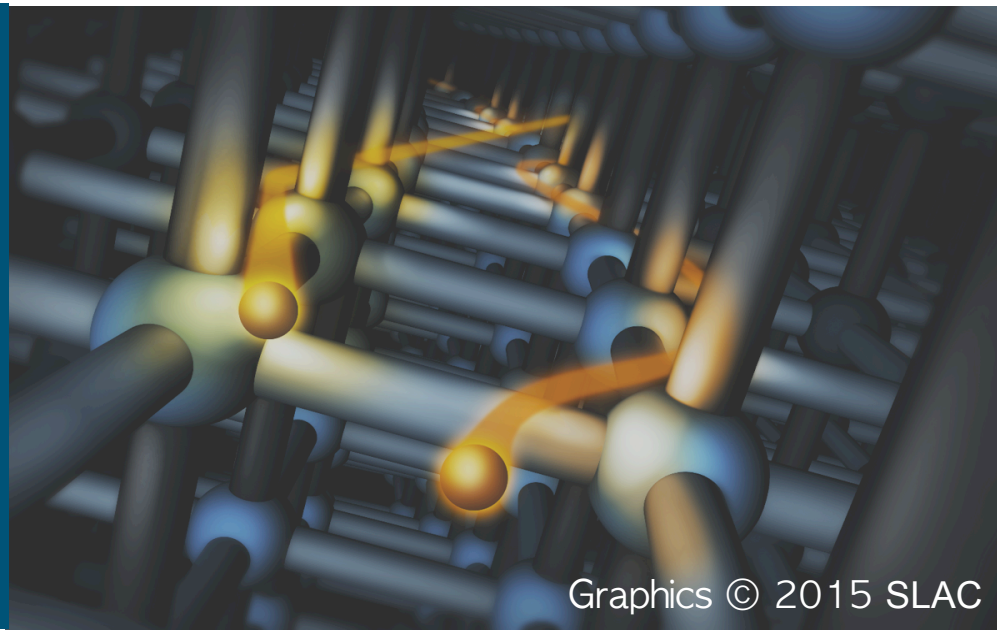
Crystal Channeling Experiments in the USA



U. Wienands (Argonne National Laboratory);

Channeling 2018

Ischia, IT

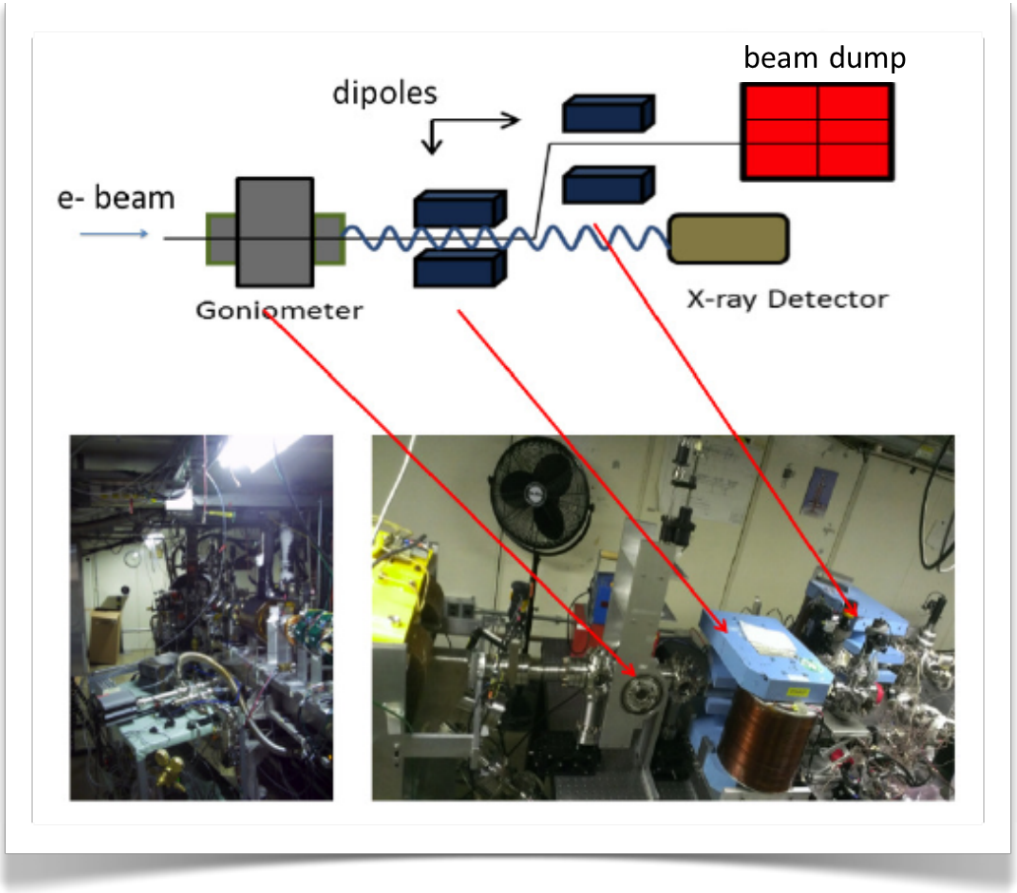
Channeling Experiments with Electron & Positrons in the USA

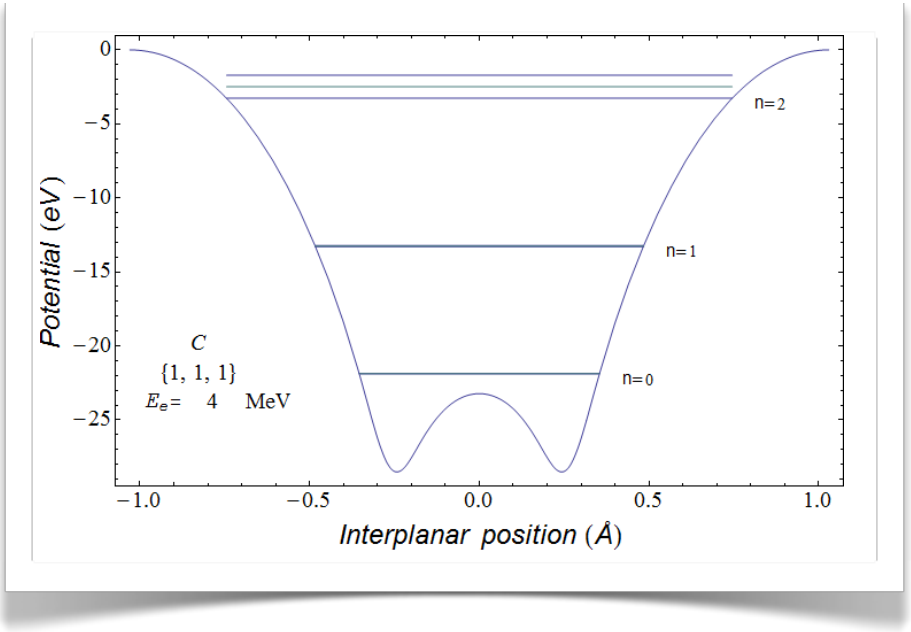
- Focusing on the radiation aspect of channeling leptons
  - Miroshnichenko et al., SLAC 1978
    - first > 10 GeV work (with positrons)
- The SLAC experiment sparked interest in the US
  - R.H. Pantell, Stanford, B.L. Berman et al., Livermore, mid-1980s:
    - Channeling radiation,10s of MeV electrons.
  - 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

Proc. FEL2013, New York, NY, 38 (2013) (Blomberg, Piot et al.)

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

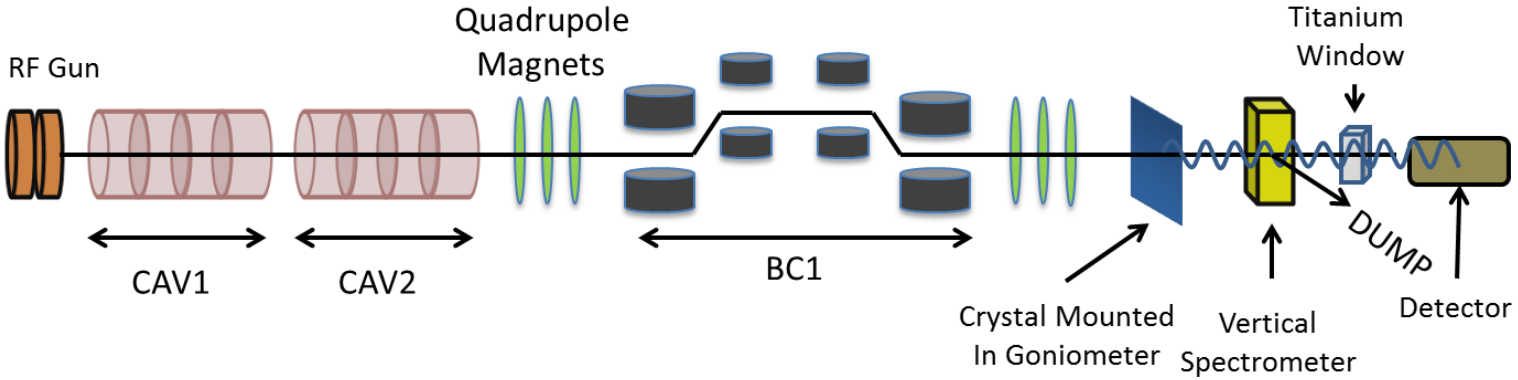


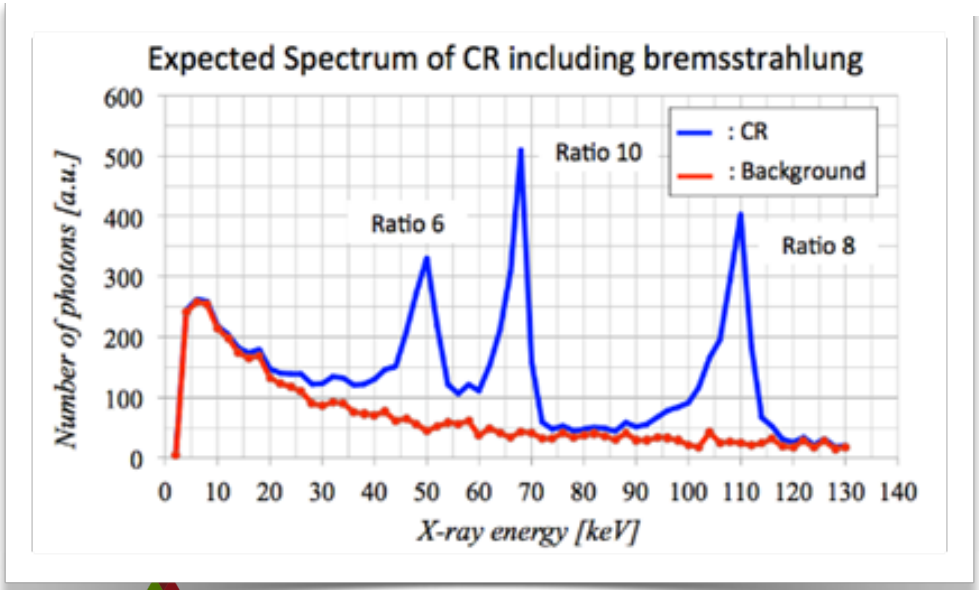


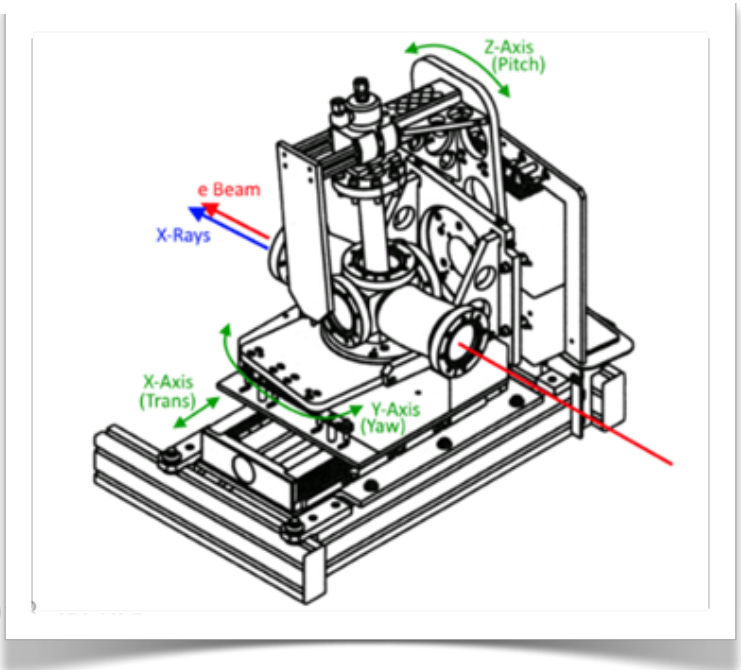
Fermilab

Proc NAPAC2016, Chicago, IL, 428 (2016), Halavanau, Sen, Shiltsev et al.

- 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)







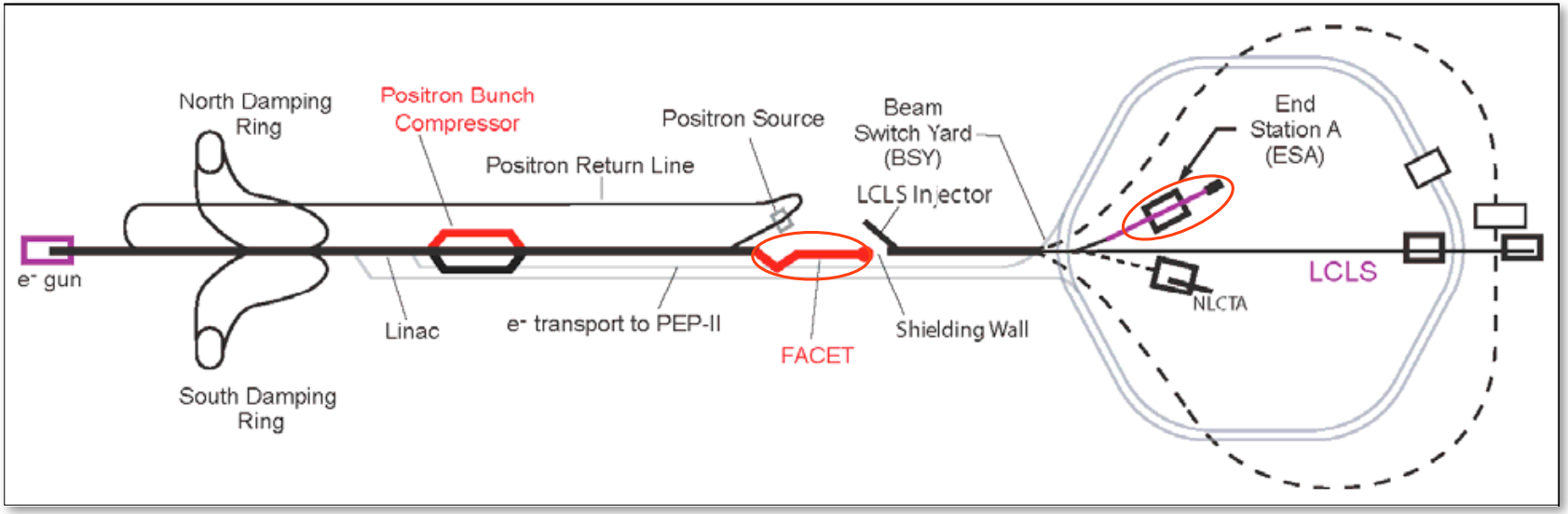
Resuming Channeling Experiments @ SLAC

- 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^-)

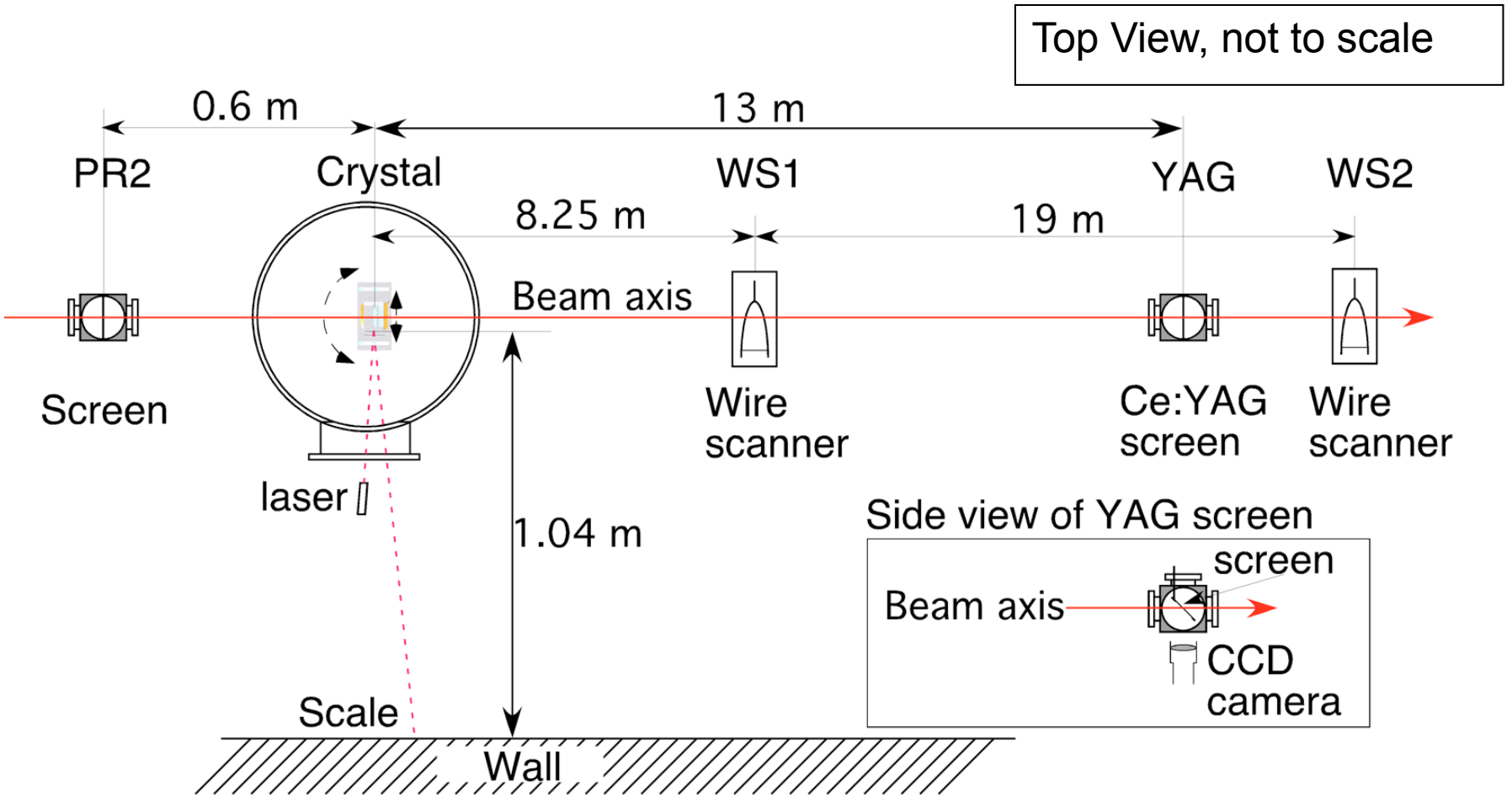
FACET and the End Station A Test Beam (ESTB) 2011…2016

- ESTB: up to 15 GeV e^-, 5 Hz, ≤ 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

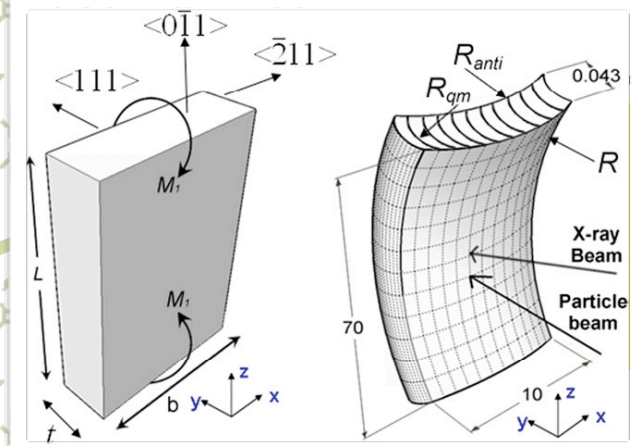


Deflection Experiments (T513, ESTB)

- Measurement of channeling parameters of 3…14 GeV e^-
  - bent crystal from U. Ferrara

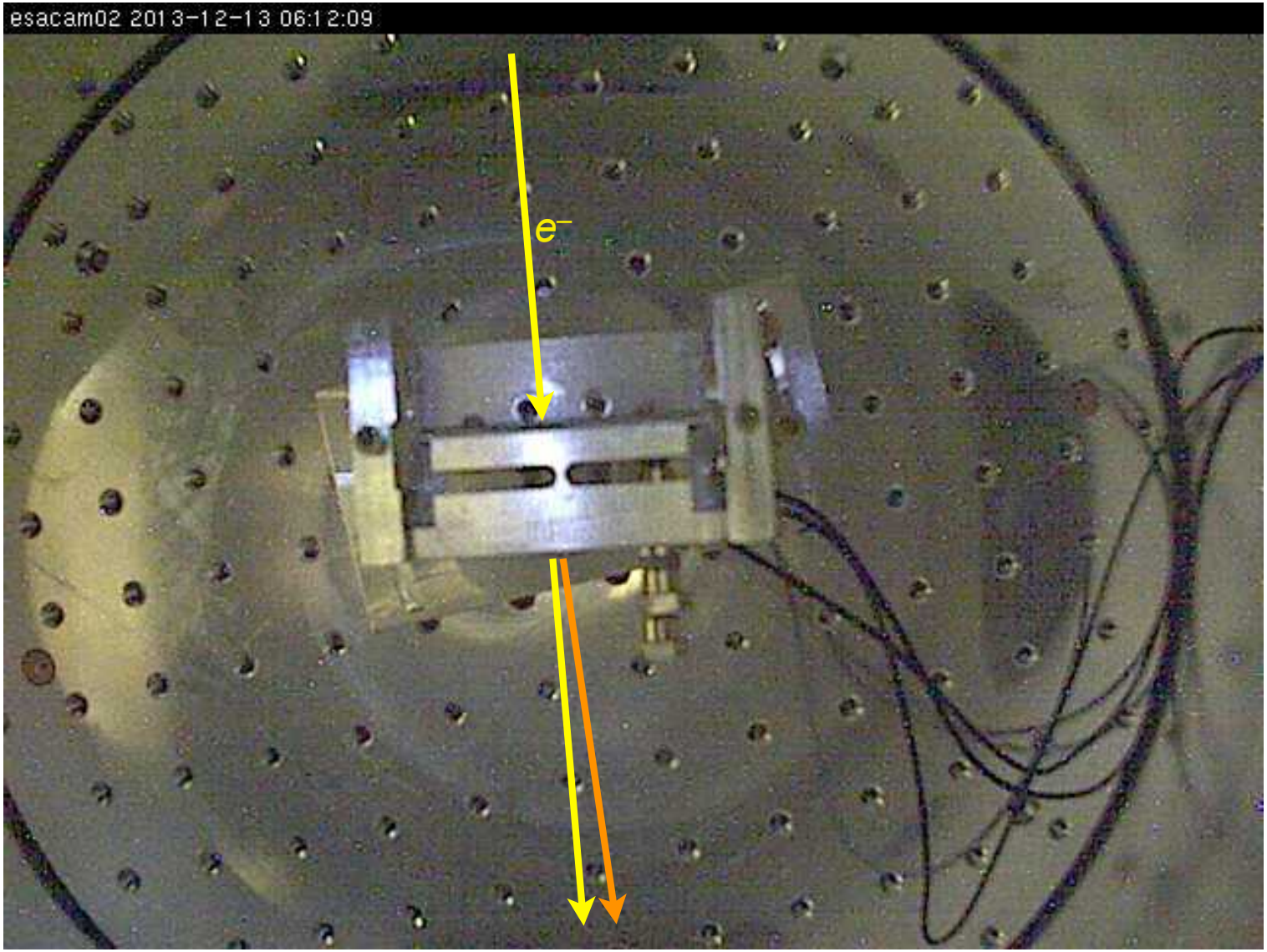


Main crystal features



- **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, ρ=0.15 m (x-ray measured). If needed I can provide a value with lower uncertainty.**

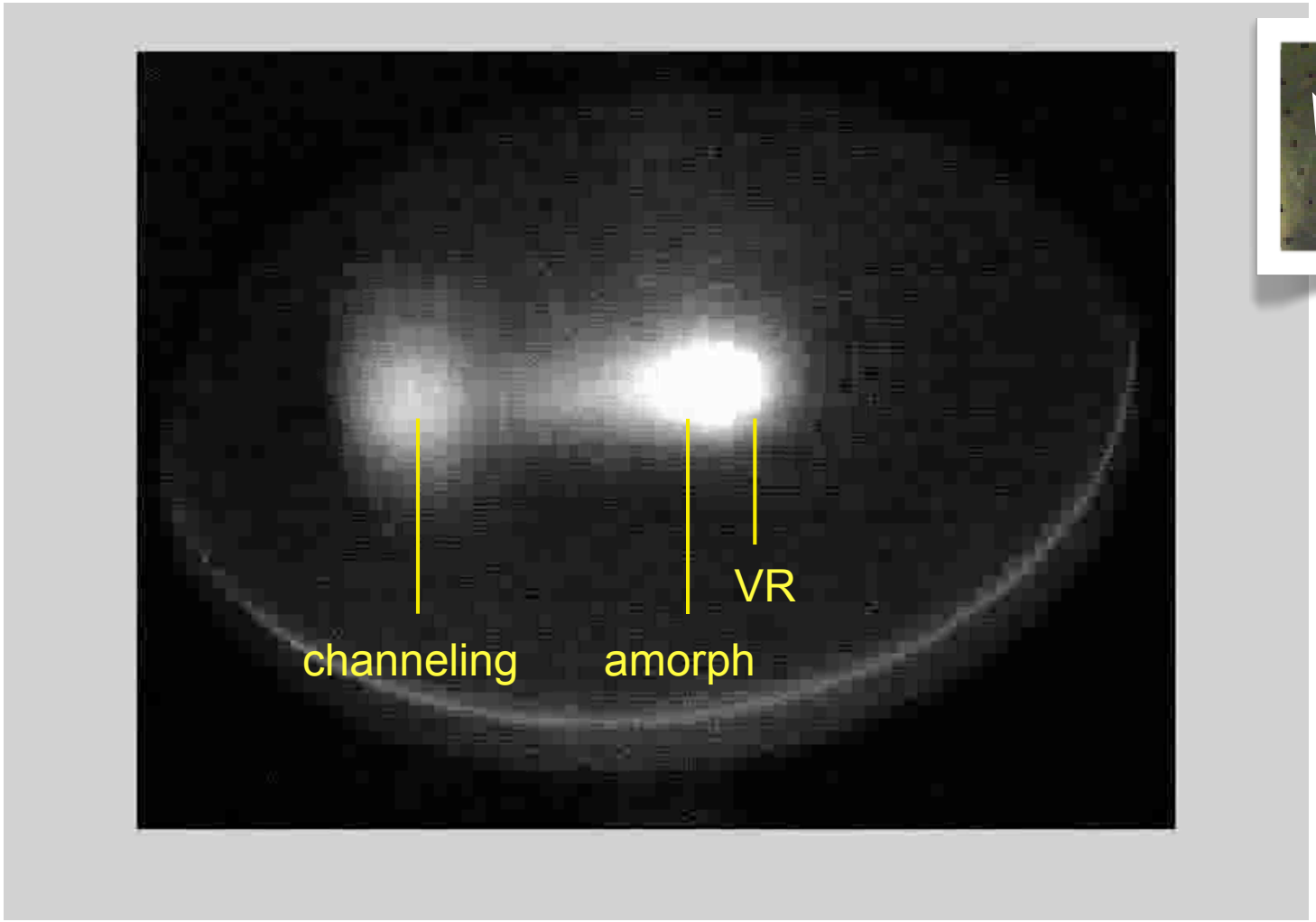
Crystal mounted in “Kraken” Chamber in ESA

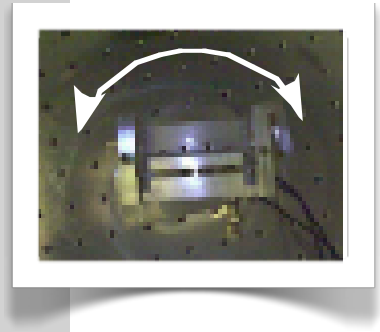


Crystal-Rotation @ 4.2 GeV

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

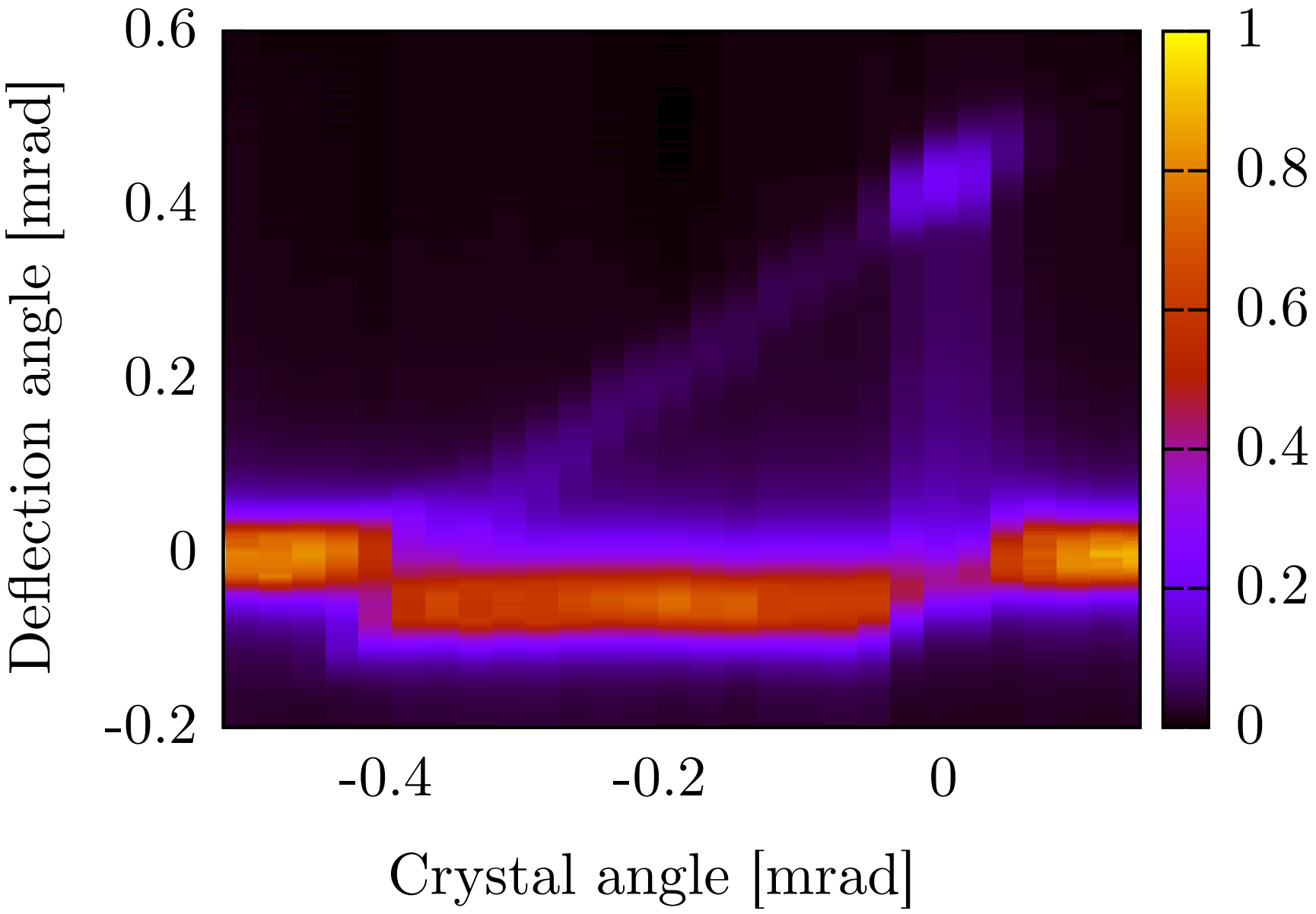
(Movie credit: T. Wistisen)





https://www6.slac.stanford.edu/news/2015-02-25-slac-led-research-team-bends-highly-energetic-electron-beam-crystal.aspx

Triangle plot (10.4 GeV)

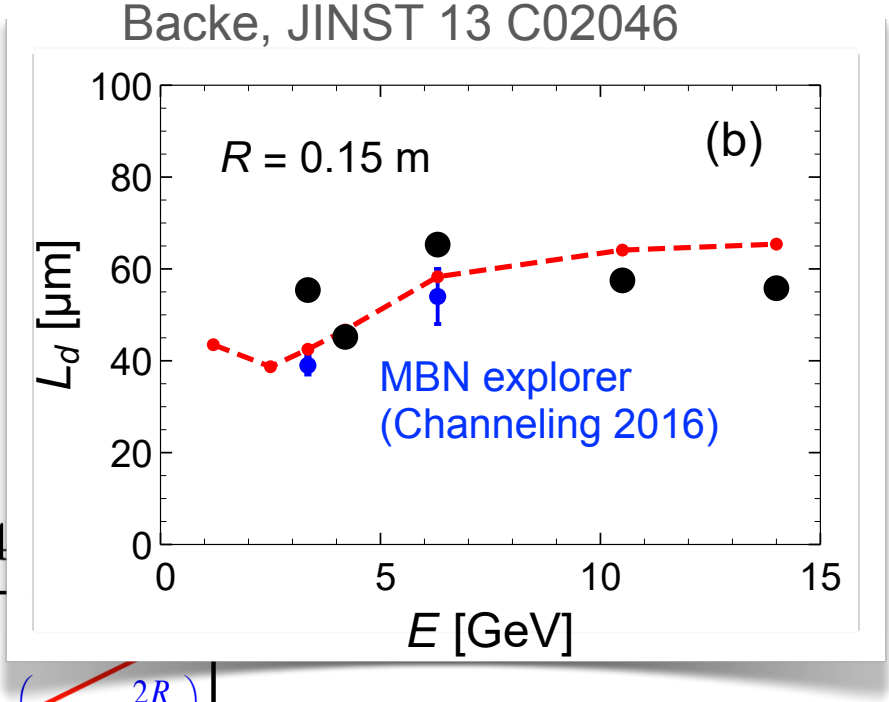


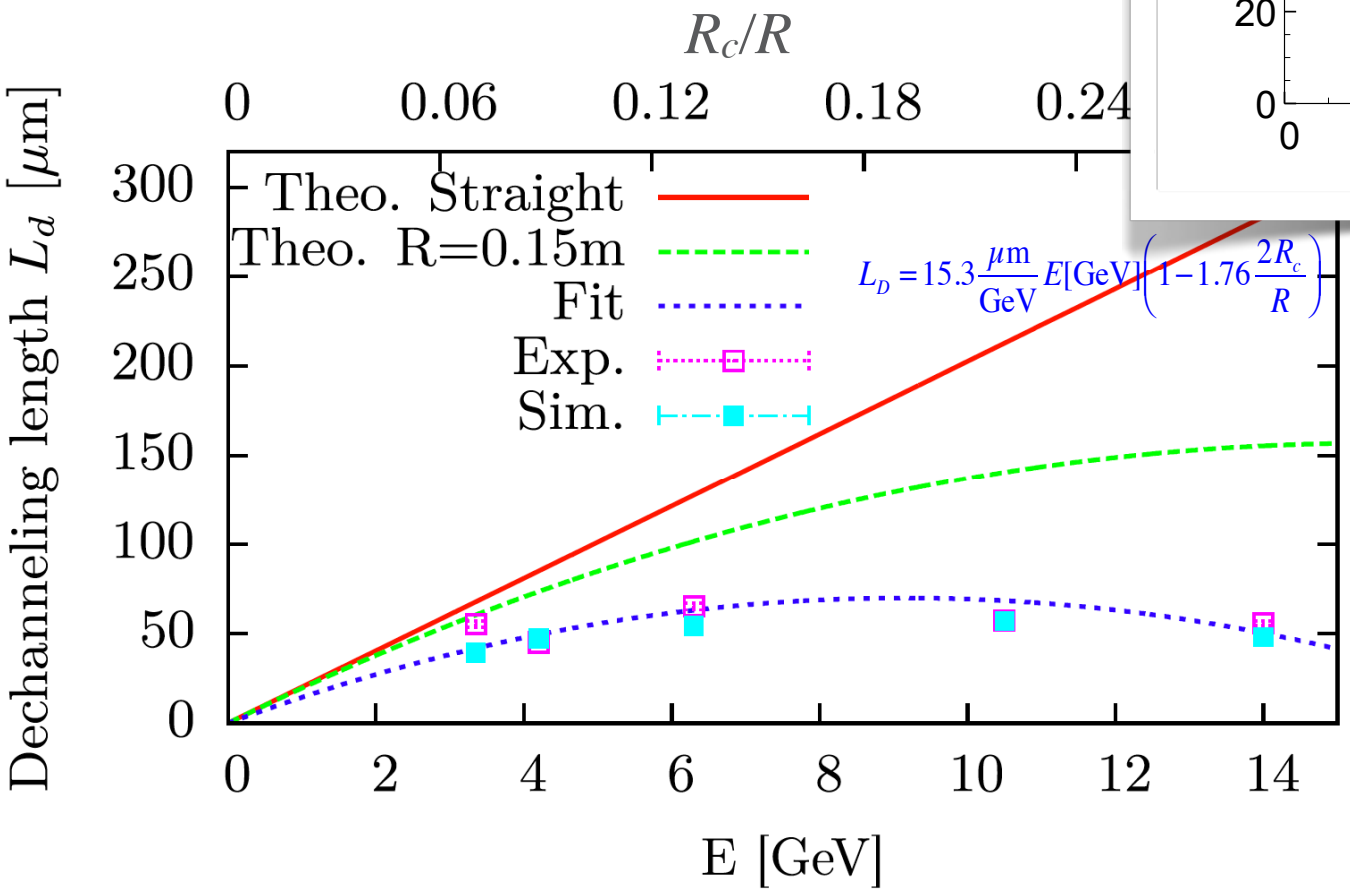
Dechanneling Length of e^-

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

Channeling efficiency 18…25%

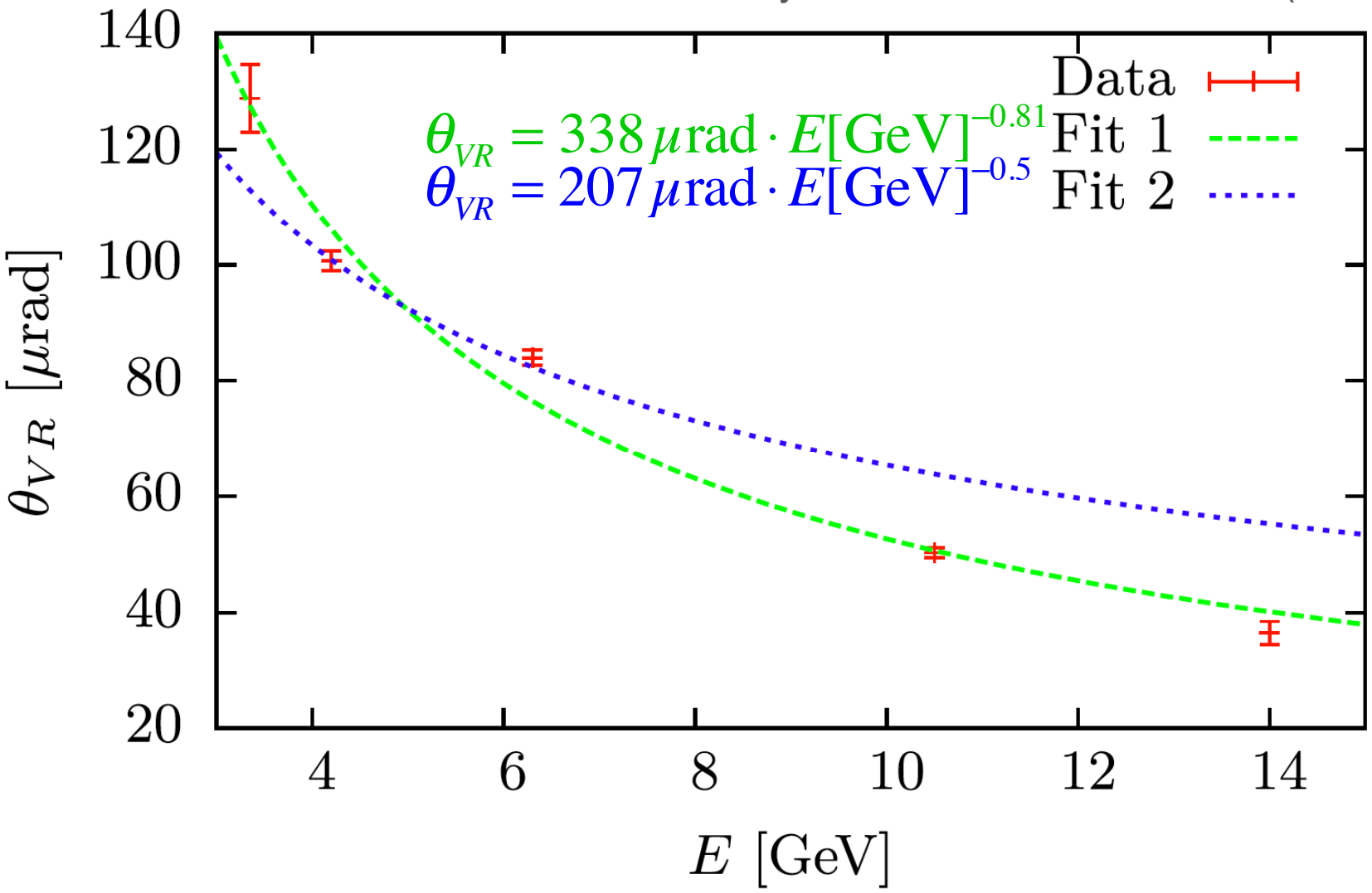
Backe, JINST 13 C02046





Volume Reflection Angle

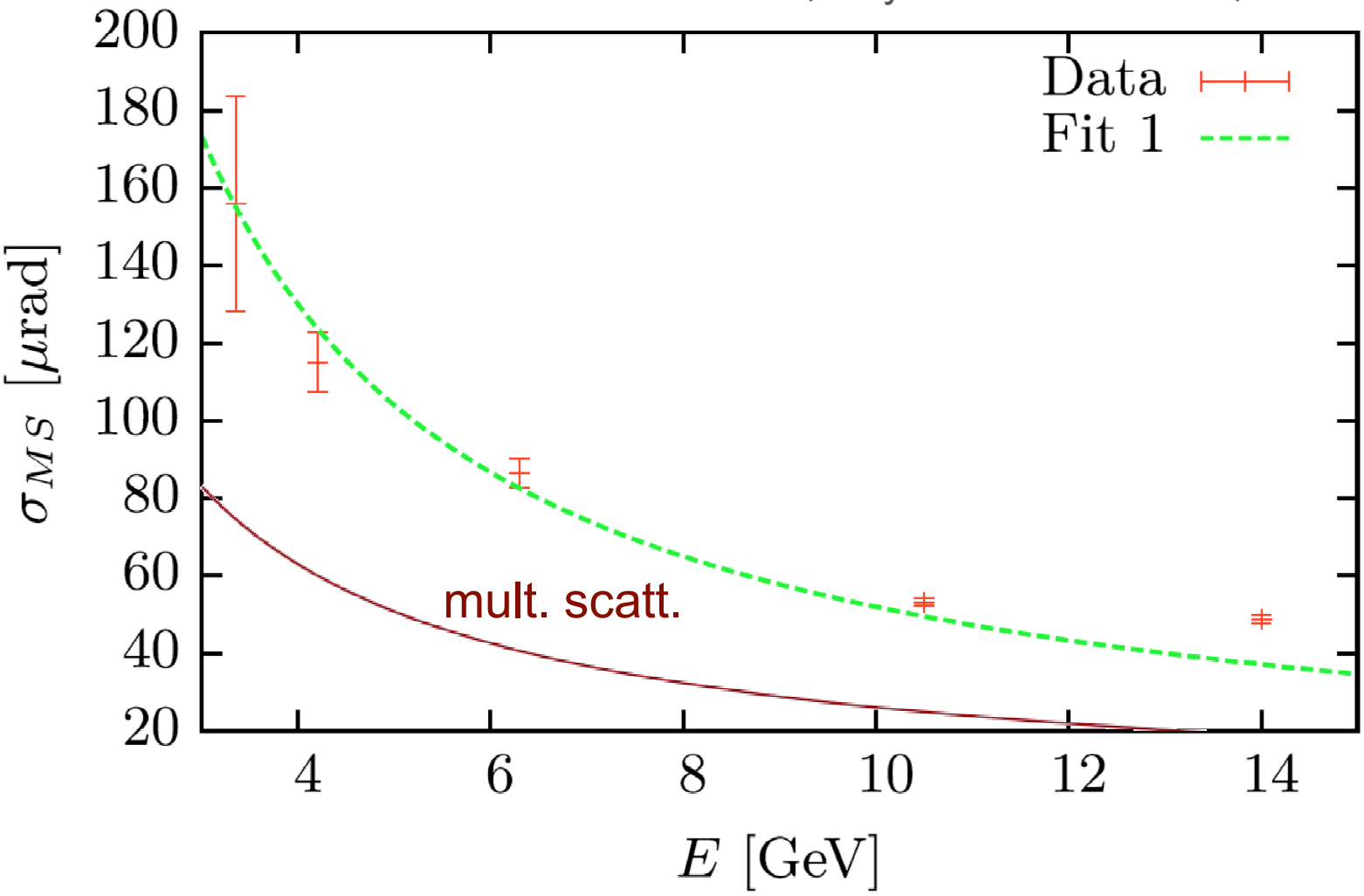
T.N. Wistisen et al., Phys. Rev. ST-AB 19, 071001 (2016)



Scattering in “Free” Direction

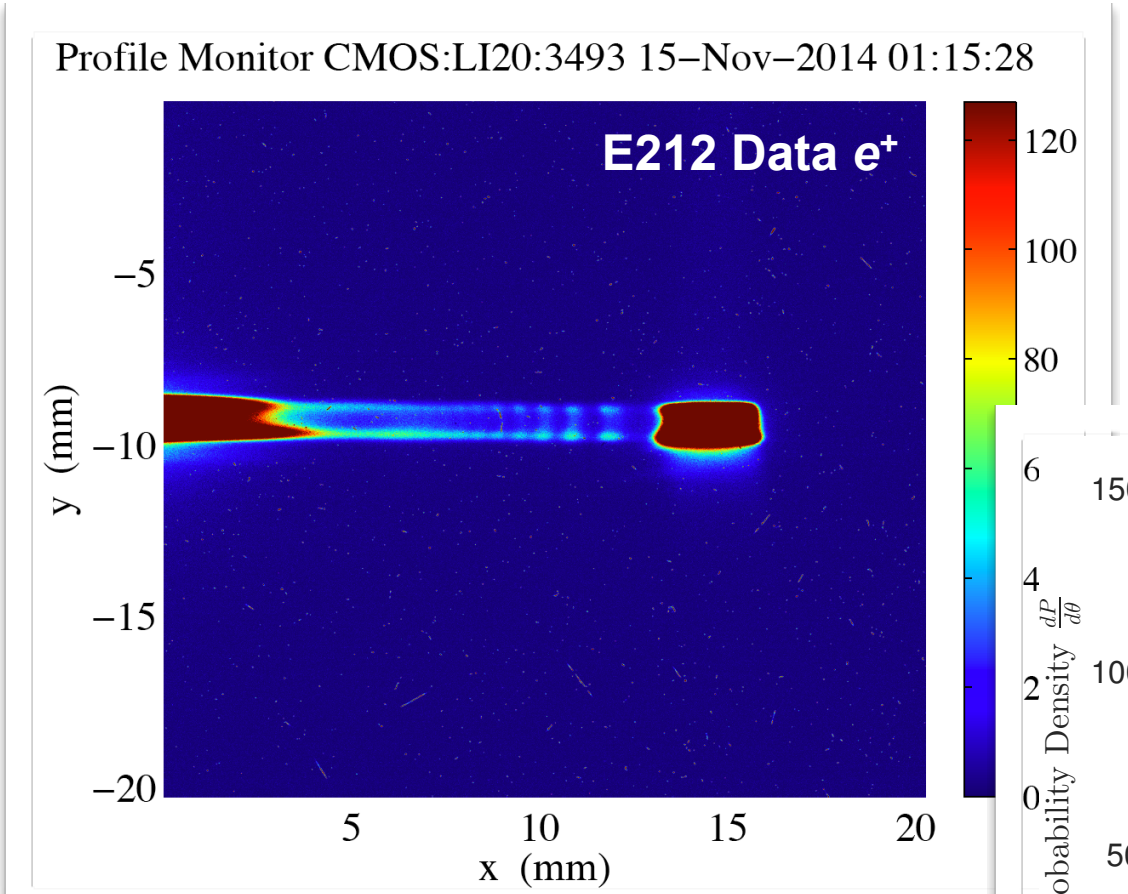
- MS in channeling is enhanced by ≈ factor 2.
  - expressed in X_0, it is a factor 1/4.

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



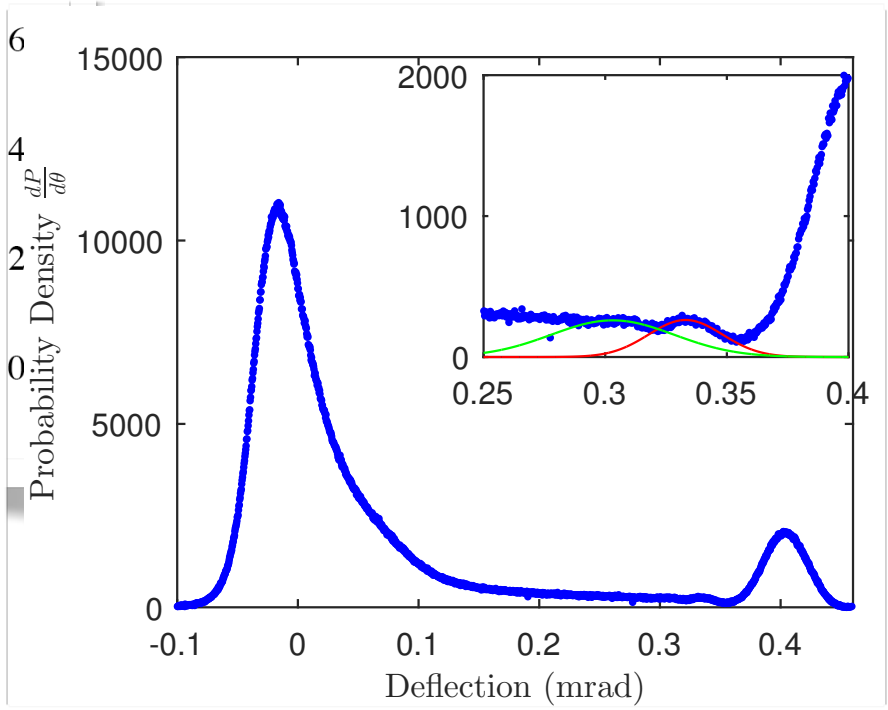
E212: First Channeling Data of 20 GeV e^+ in Bent Crystal

- Raw data



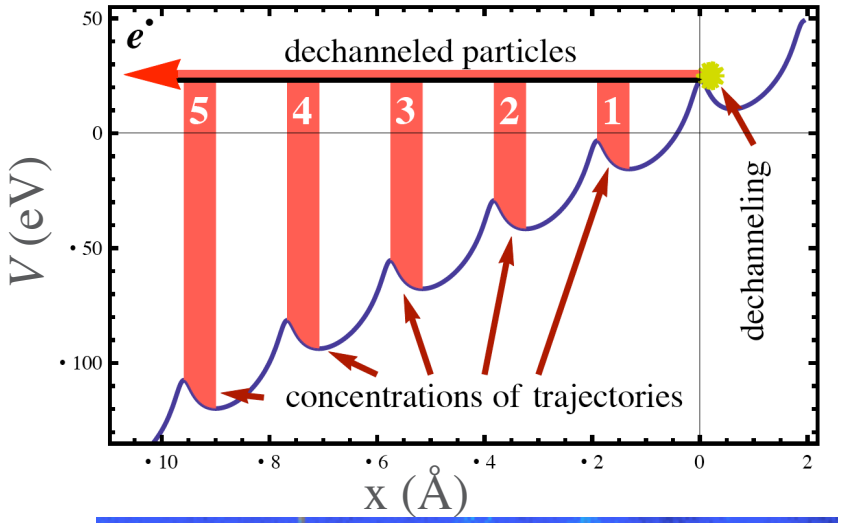
20.35 GeV e^+
10^{10} e^+/pulse

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



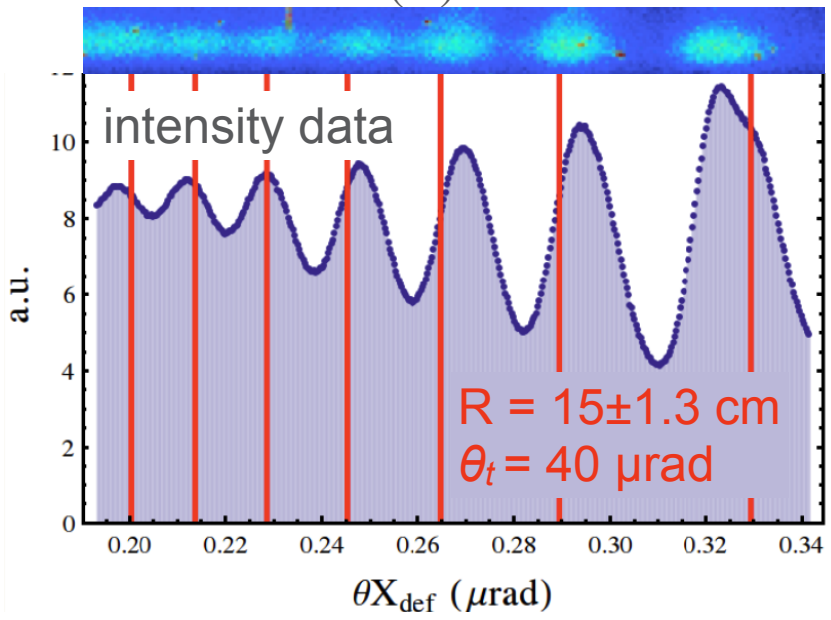
Analysis of the "Quasi-Channeling Oscillations"

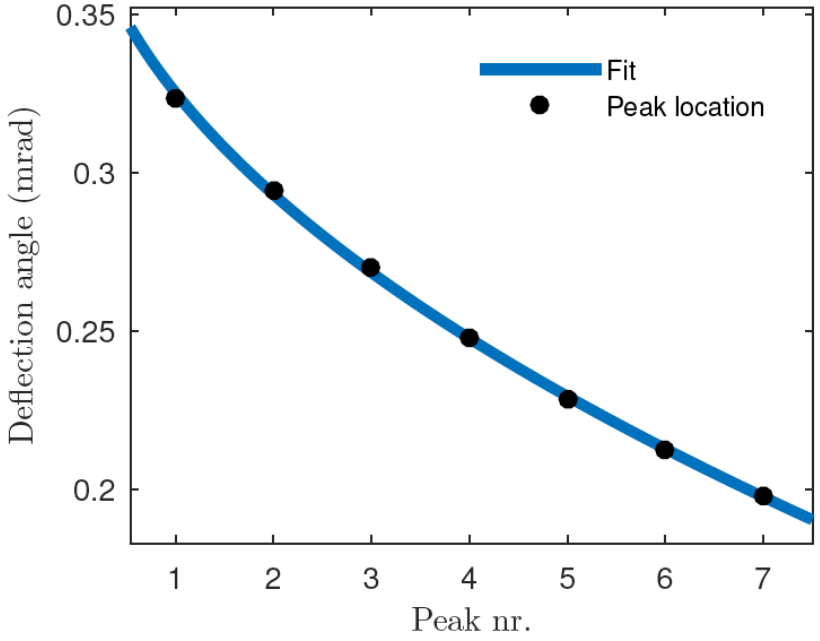
A. Sytov et al., Eur. Phys. J. C (2016) **76**: 77
Wistisen et al., Phys. Rev. Lett. **119**, 024801 (2017)



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

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



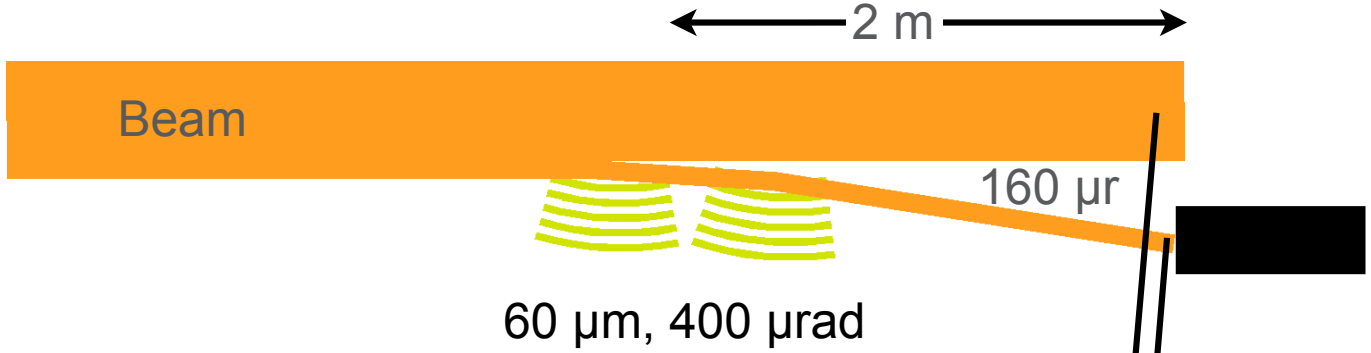


Summary of Deflection Results

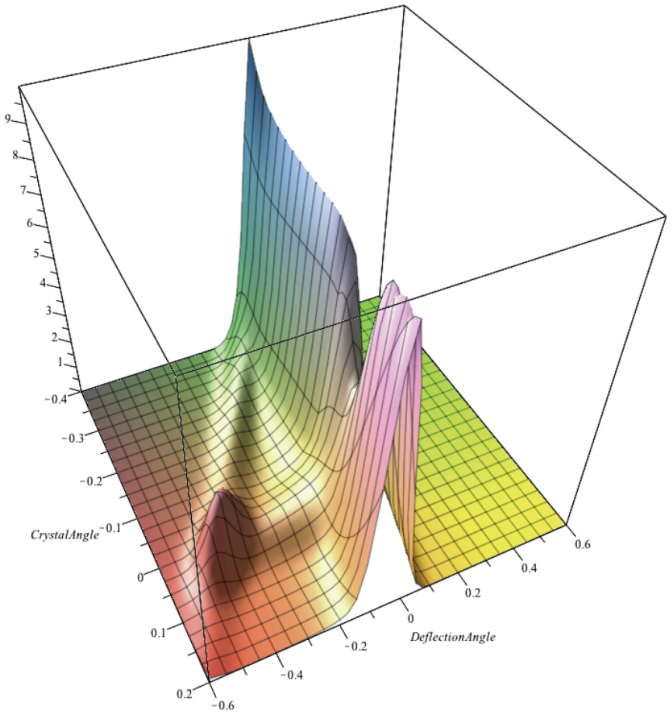
- Channeling efficiency ≈ 18…24 %, VR up to 95%
- Dechanneling length ≈ 40…60 μm
  - roughly independent of the beam energy in our range
- Surface transmission 57% (6.3 GeV)…65% (3.35 GeV)
  - calc: 57% @ 6.3 GeV
- Scattering is enhanced in the vertical plane for channeled particles
  - by roughly a factor 2 (X0 –> X0/4)
- Quasi-Channeling oscillations observed with e^+ (and hints with e^-).
  - dechanneling length with electrons approx. 350 μm.

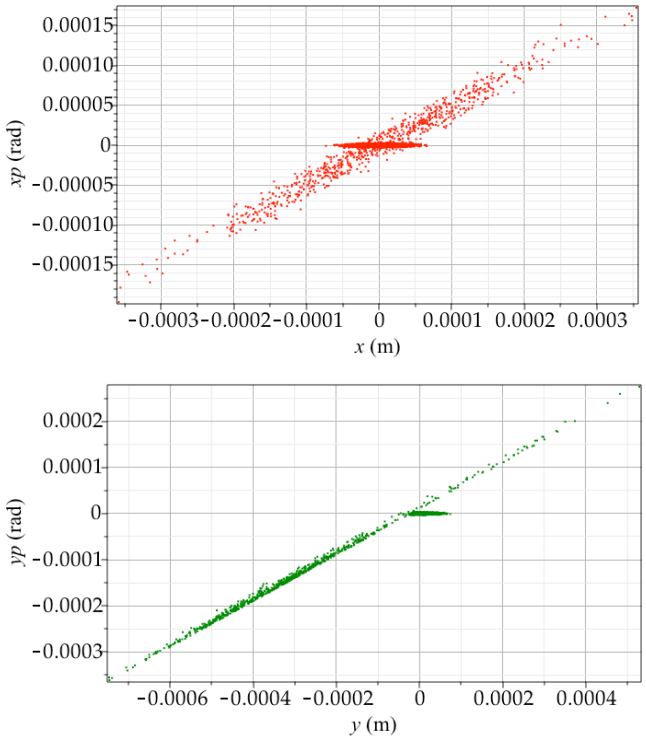
VR Collimator Concept

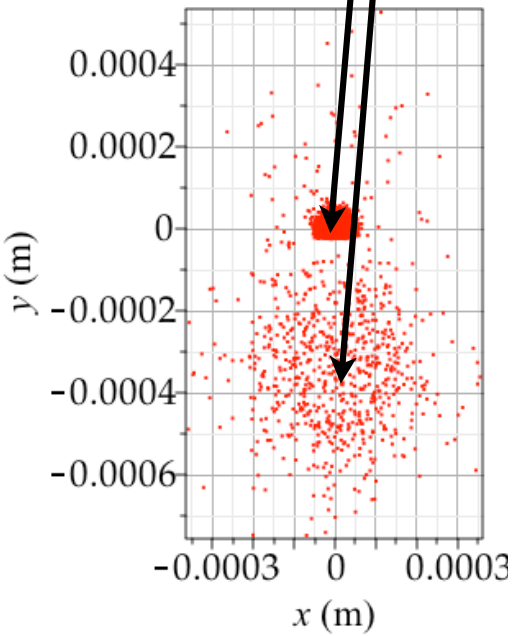
- The T513 data can be used to investigate beam collimation:
- APS-U: 6 GeV, 2 T513 crystals in series



pdf to generate deflections

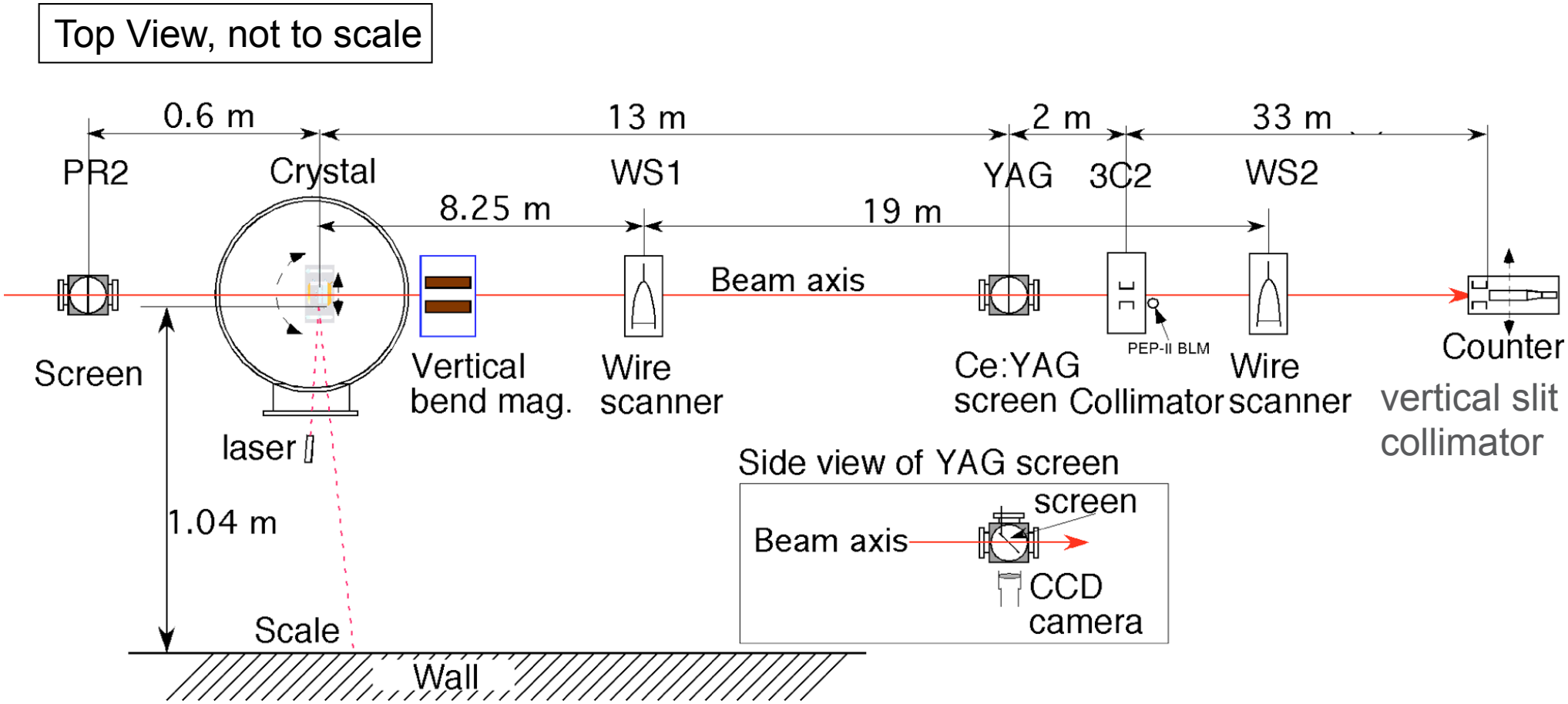






Radiation Experiments

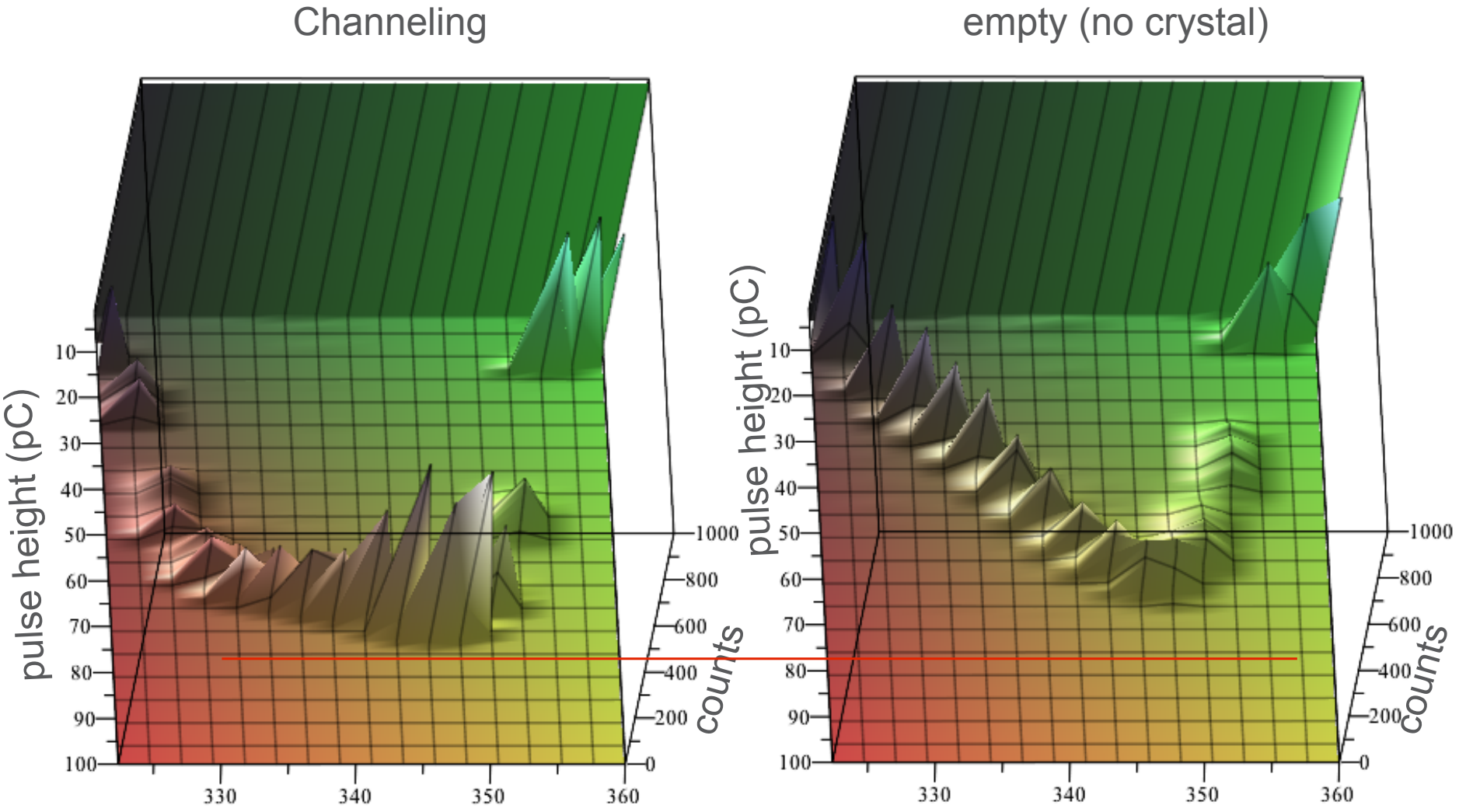
- ESTB Setup augmented with γ counter and deflector.



High-Intensity spectra

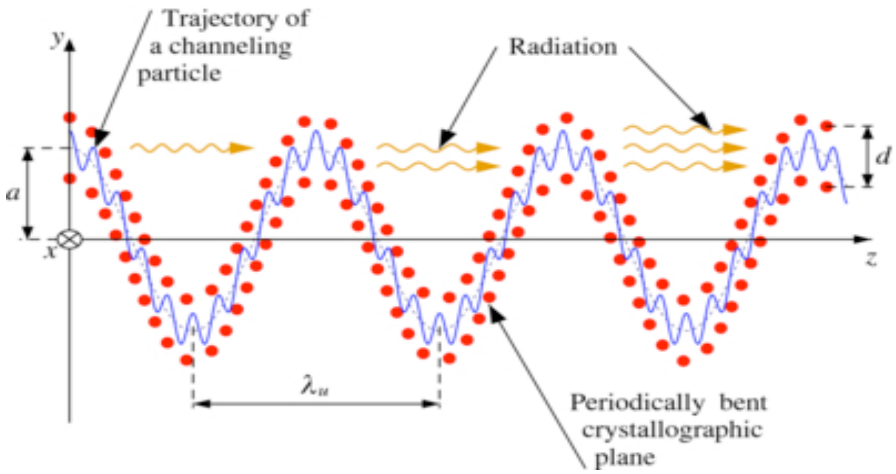
many photons per linac pulse

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



Monolithic Undulator

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

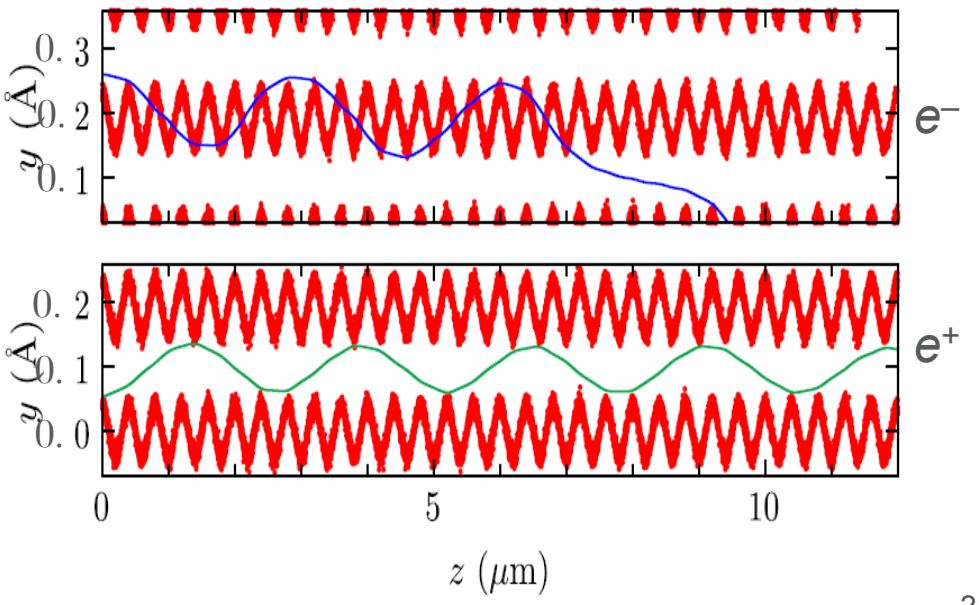


Small amplitude, short period (SASP, Kostyuk 2014):

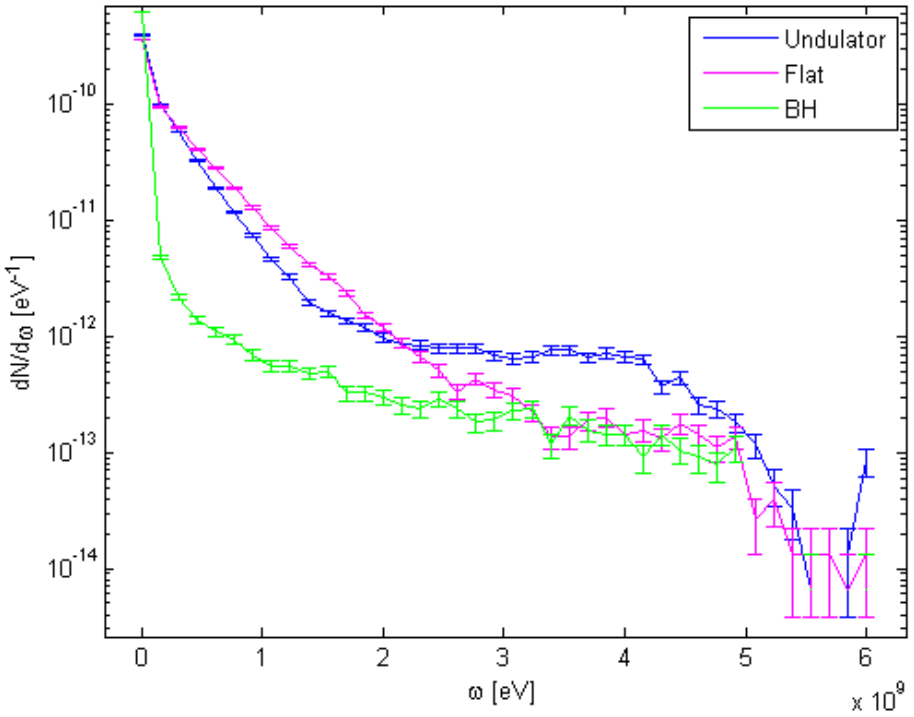
"Slow" betatron oscillations, fast undulations

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

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

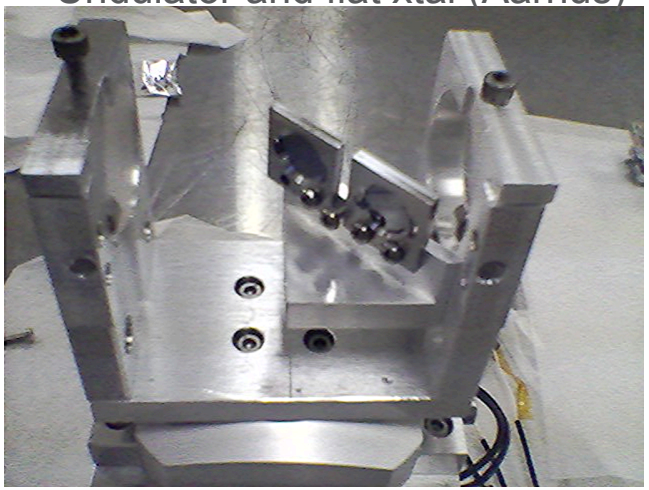


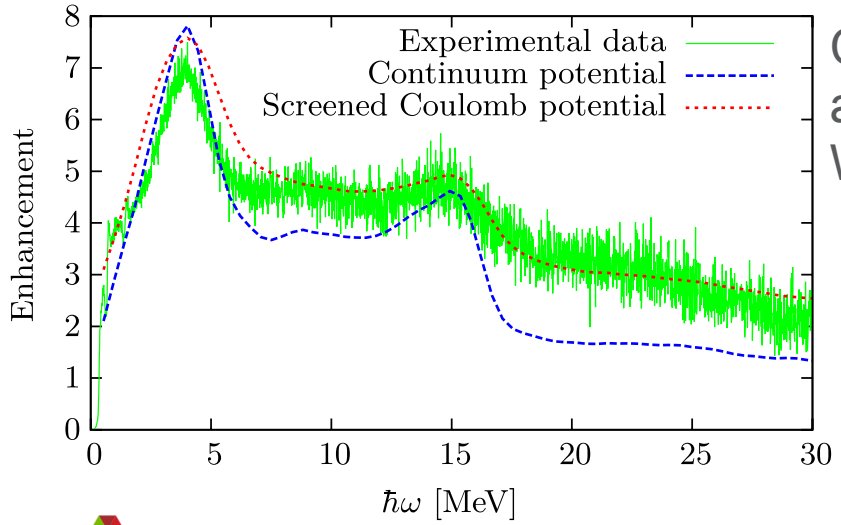
Expected spectra, 16 GeV



(Wistisen, 2016)

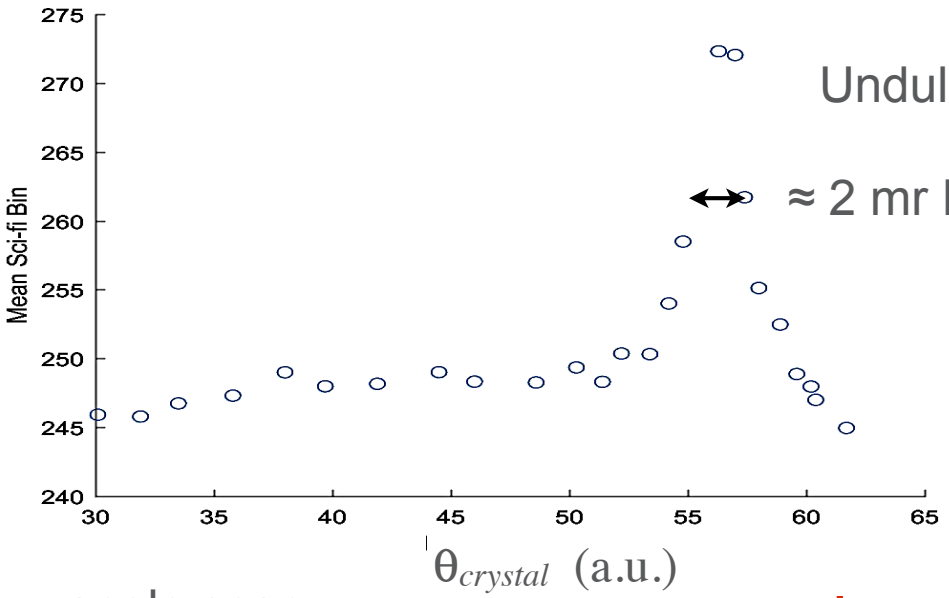
Undulator and flat xtal (Aarhus)





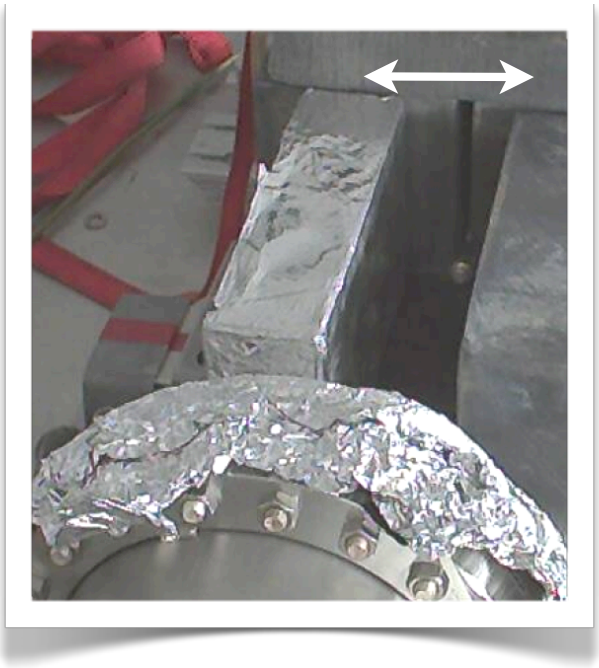
Comparison of spectrum of similar crystal at 855 MeV (MAMI expt., Wistisen et al., PRL **112**, 254801 (2014))

Angular Distribution Aligned – Amorph

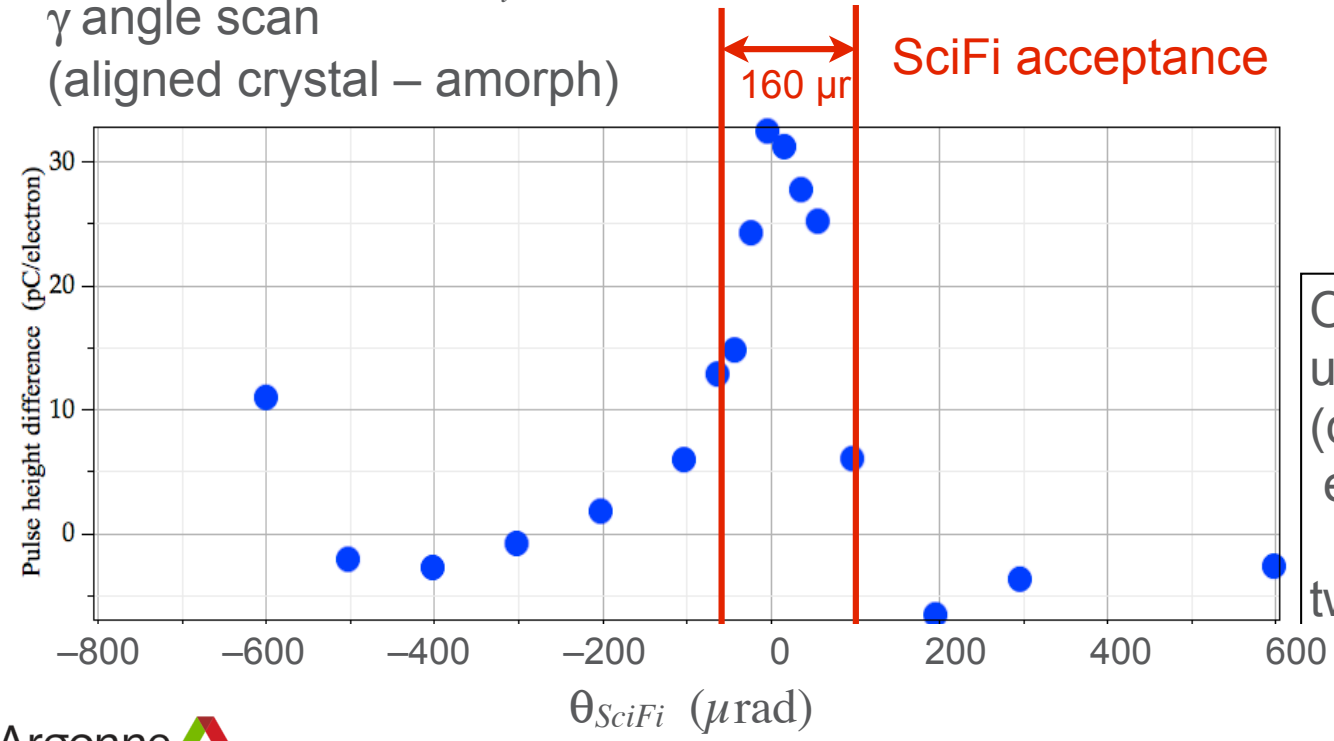


Undulator crystal angle scan

≈ 2 mr FWHM



γ angle scan
(aligned crystal – amorph)



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

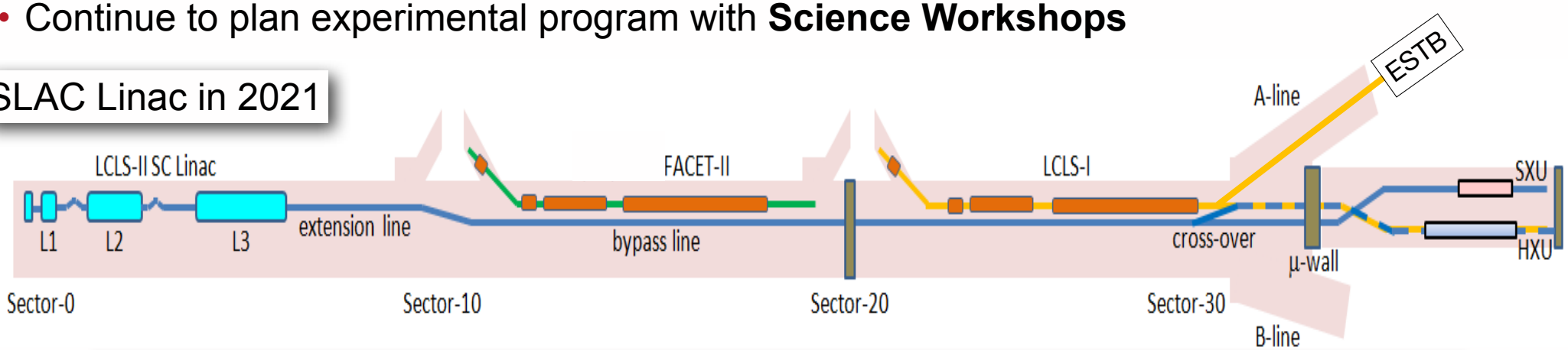
- We will have our next E212/T523 run in November

- 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

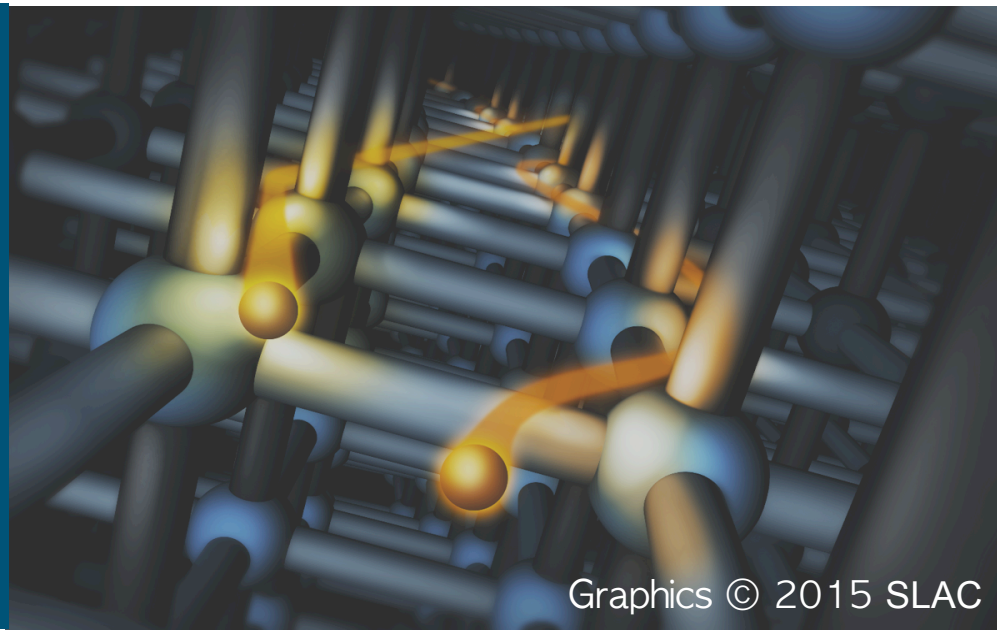
- FACET stopped running in April 2016 to begin LCLS-II construction
- Over the next few years FACET-II will add new capabilities:
  - LCLS style photoinjector with state of the art electron beam (low emittance, small divergence)
  - Flexibility e.g. low-charge mode or 'two color' operation for two-bunch PWFA
  - Nominal $\mathbf{e^-}$ parameters: 10GeV, 2nC, 15kA, 30Hz (**2019**) → Beam quality
  - Nominal $\mathbf{e^+}$ parameters: 10GeV, 1nC, 6kA, 5Hz (**2021**) → Positron Acceleration
  - External injection → Staging studies, ultra-bright sources
- Continue to plan experimental program with **Science Workshops**

SLAC Linac in 2021



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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U. Uggerhøj, R. Mikkelsen* (U. Aarhus, DK);

T. Wistisen* (now Max-Planck Institute, Heidelberg, D)

A. Mazzolari, **E. Bagli*, L. Bandiera***, G. Germogli*, A. Sytov*, V. Guidi (U. Ferrara, IT);

R. Holtzapple, S. Tucker*, K. McArdle* (CalPoly, US)

* Student/postdoc

**My thanks go to our collaborators;
they are the ones who made these experiments work.**

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Danish Council for Independent Research FNU,
INFN**

And to Prof. Dabagov for his support.