Bent Crystal Proton *Collimation*: Now A Reality

Tevatron T-980 Experiment

FNAL, BNL, CERN, IHEP, INFN, PNPI

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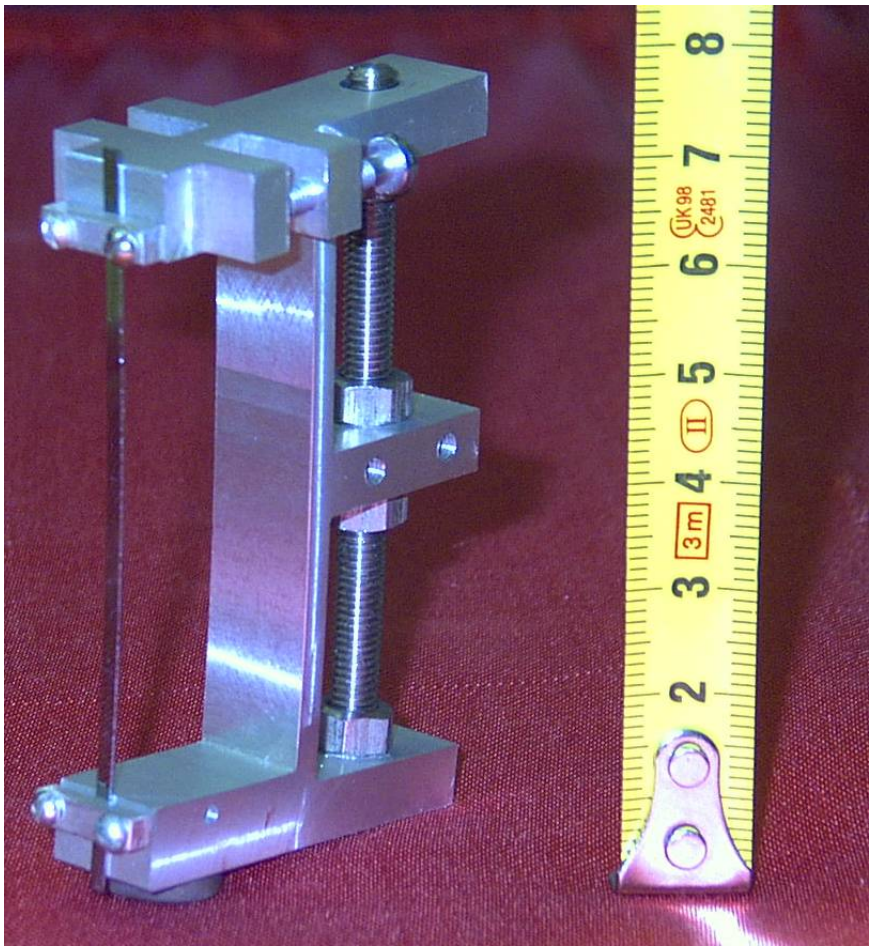
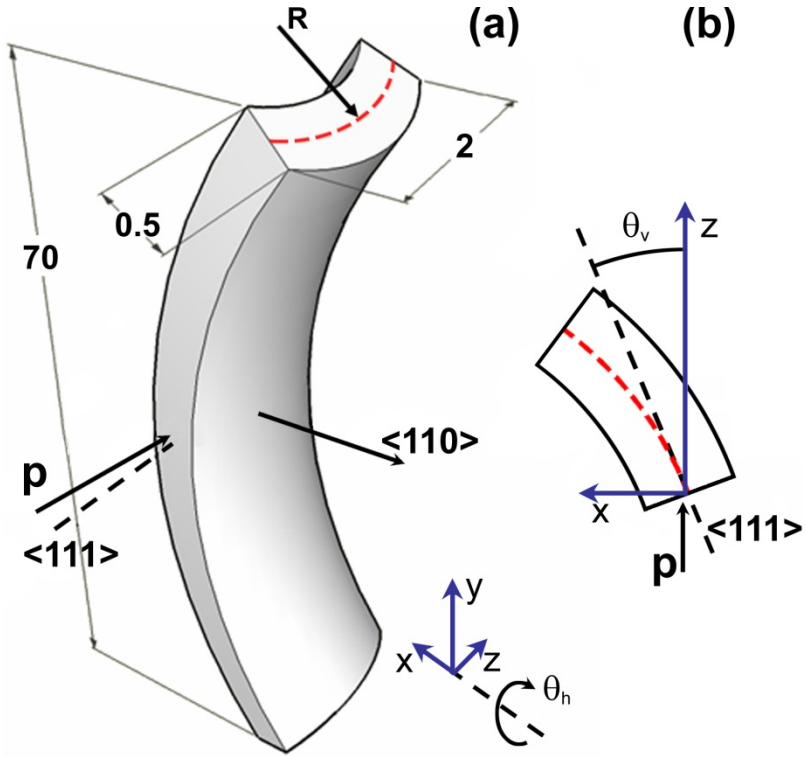
Outlook

- Physics
- Experiment
- Results
- Summary and Plans

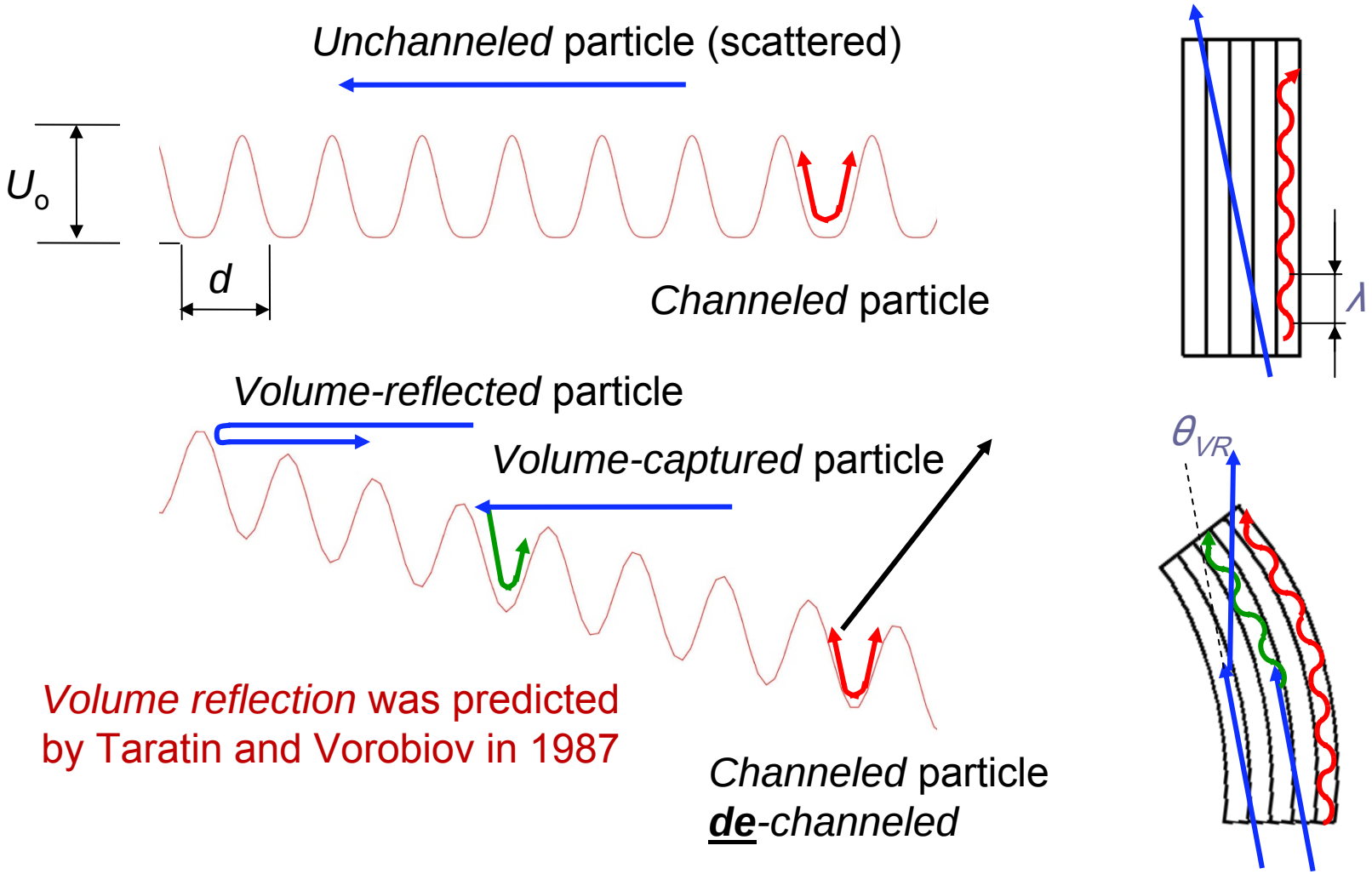
What is *bent crystal*?



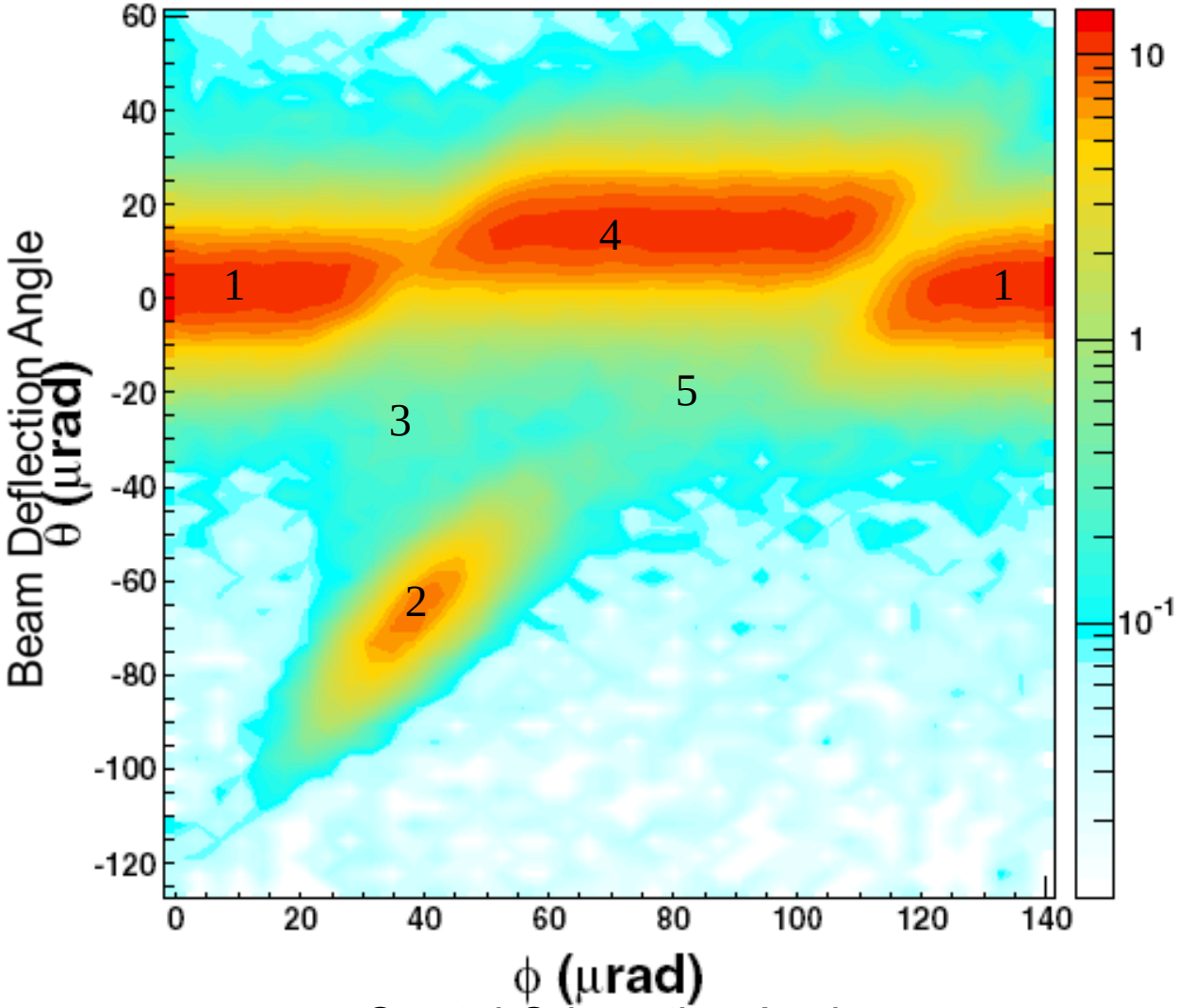


Crystal bending is accomplished through *anticlastic* deformation

Five (!) Processes in Crystals



Single Pass Observations: SPS Beamline



1. Primary p+ beam
2. Channeling
3. Dechanneling
4. Volume reflection
5. Volume capture

Note the difference in acceptance:

Channeling <10 μrad

Vol-reflection ~100 μrad

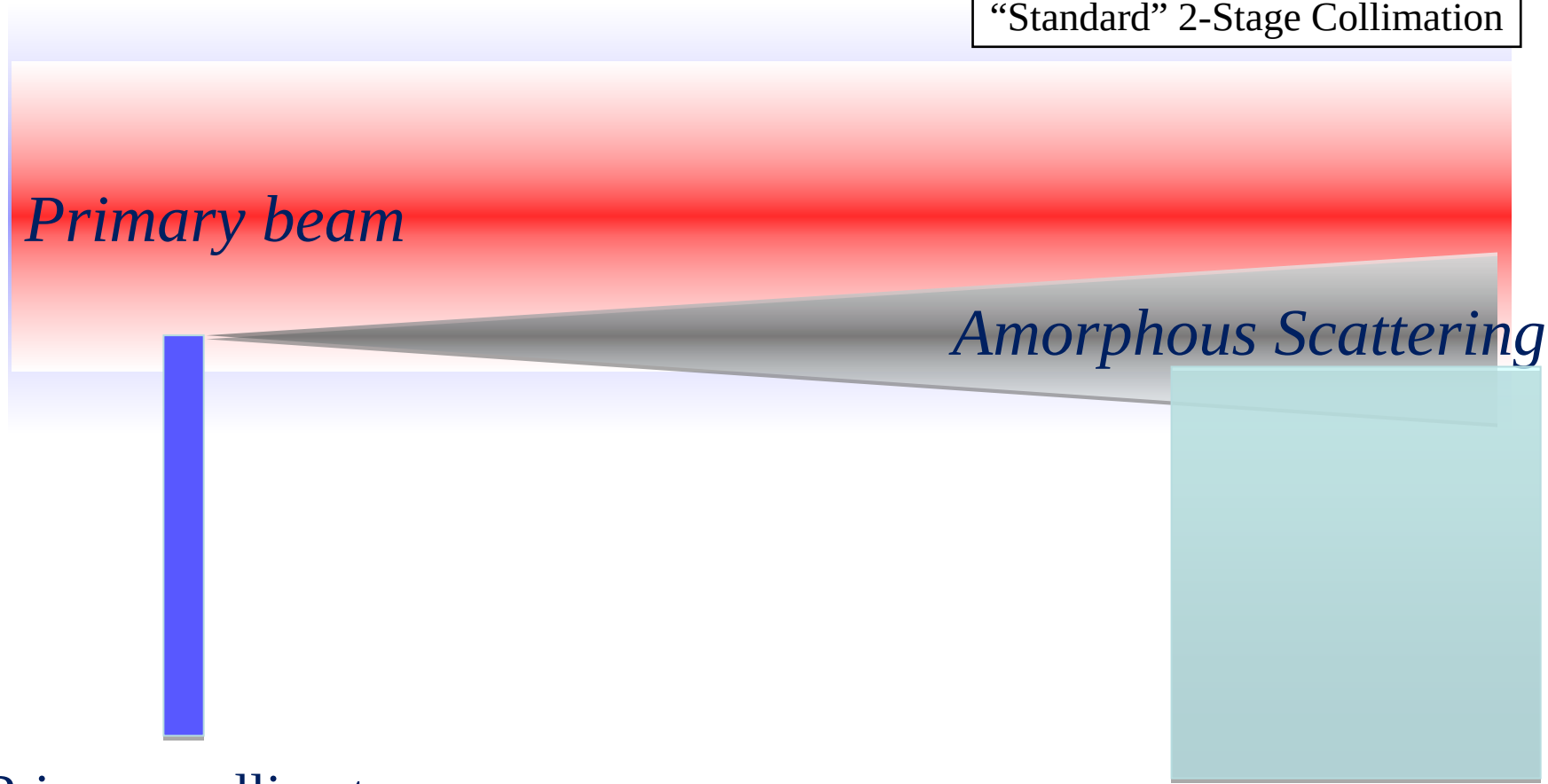
.. and m.b. higher **efficiency**

...but smaller angle

PRL **97** (2006) 144801
PRL **98** (2007) 154801
PRST **11** (2008) 063501

Circulating Beam Collimation

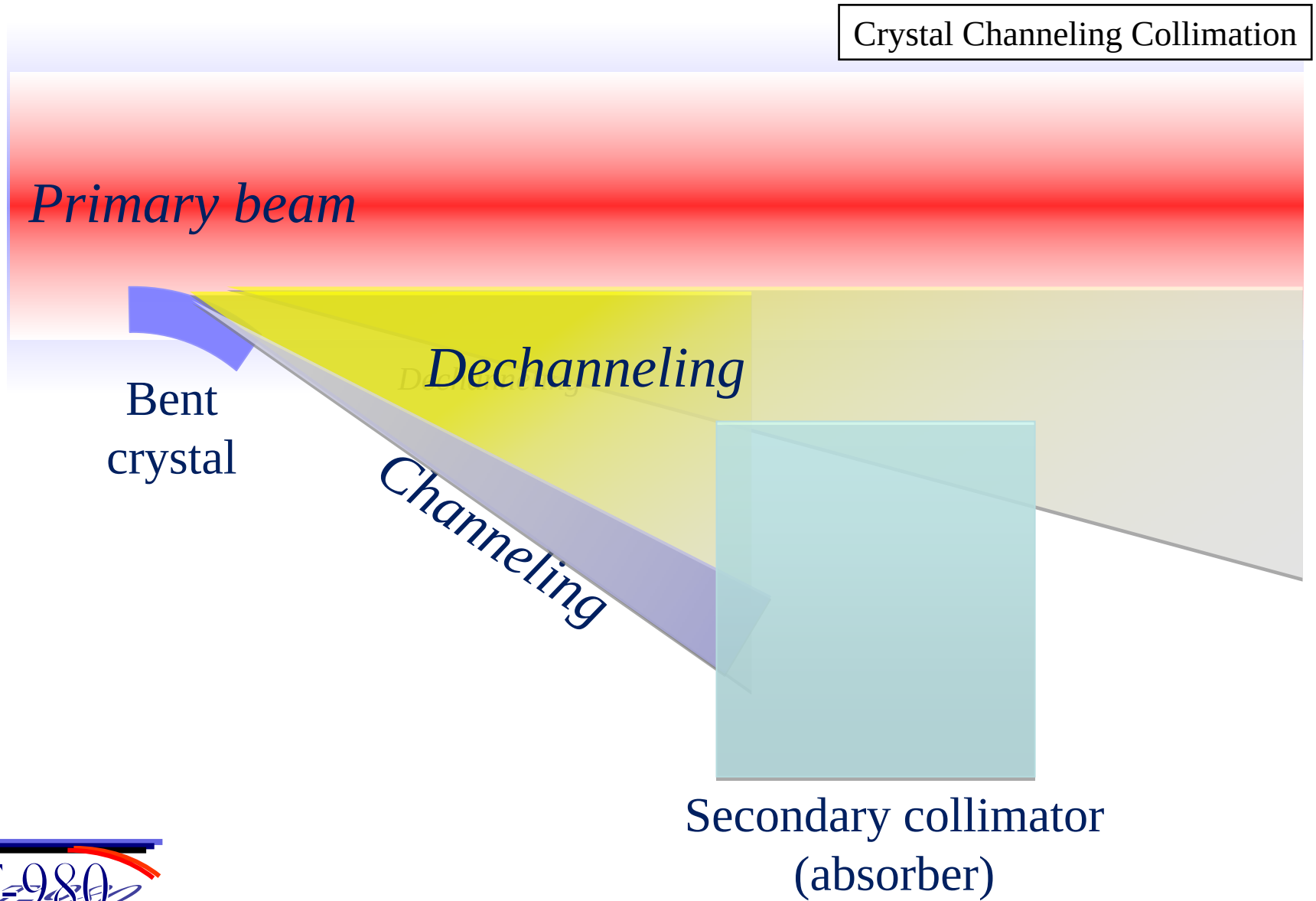
"Standard" 2-Stage Collimation



Primary collimator
(scatterer)

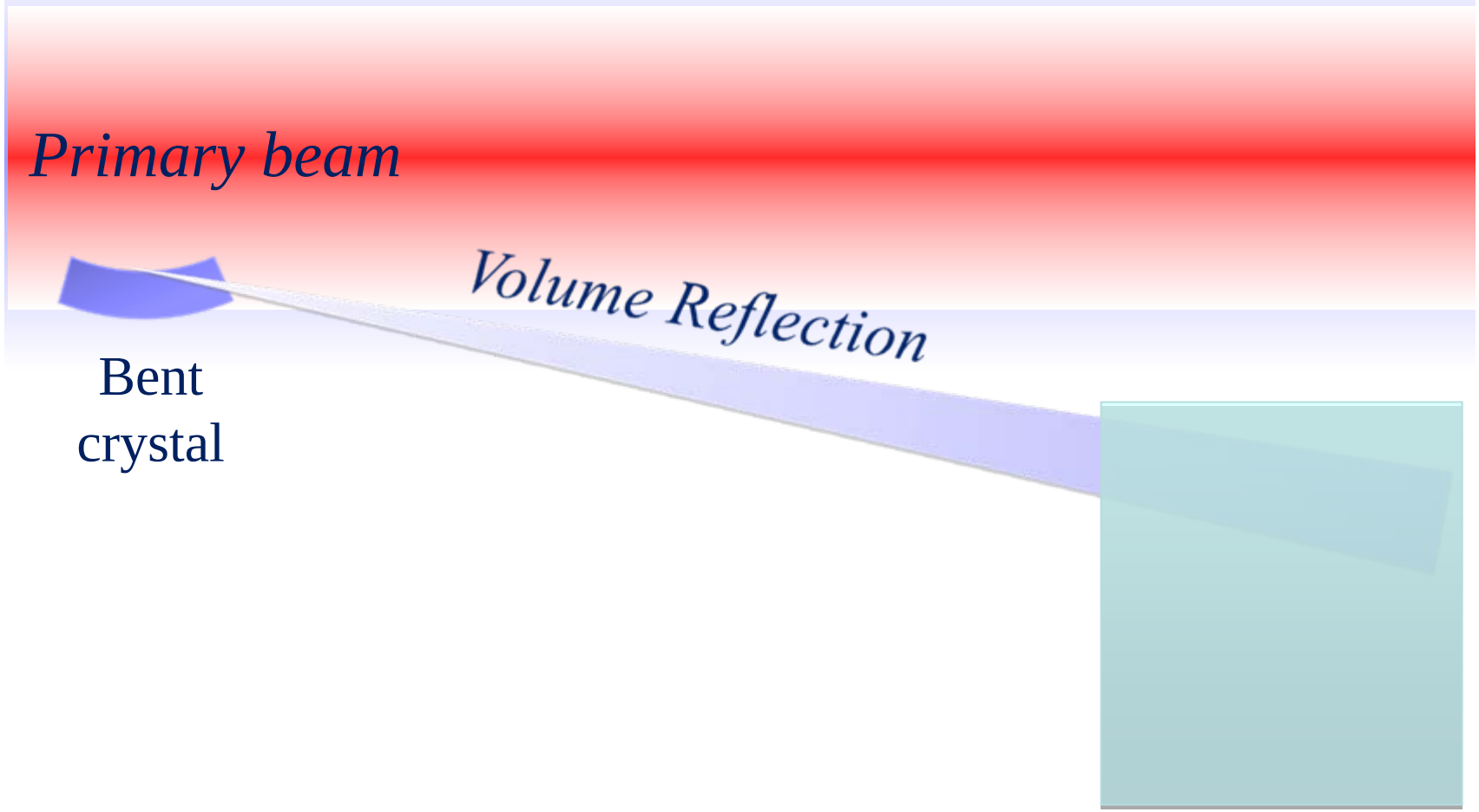
Secondary collimator
(absorber)

Collimation by Crystal Channelling

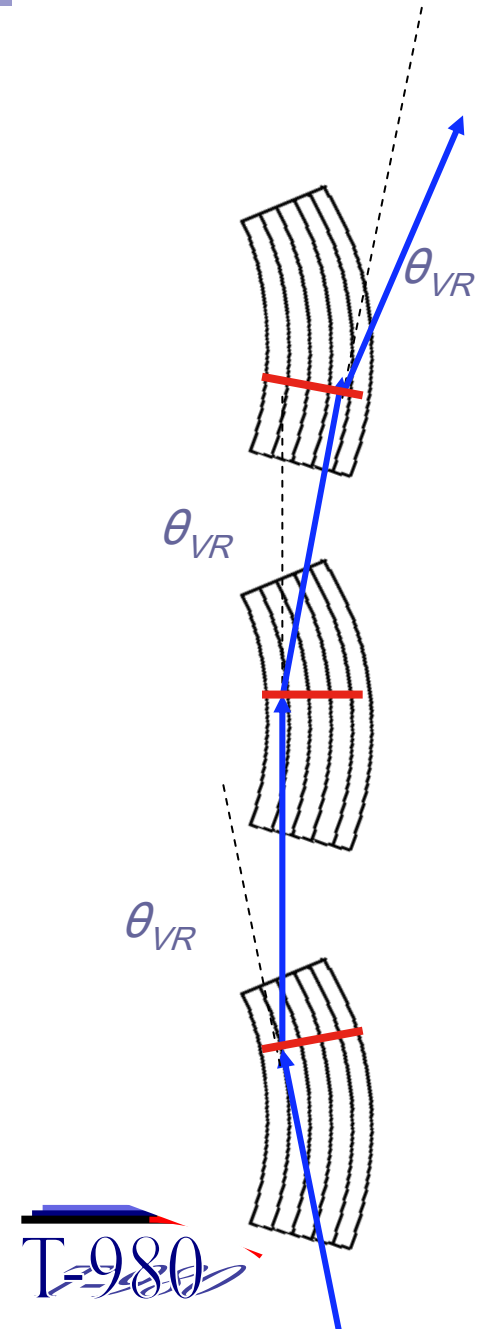


Collimation by Volume Reflection

Crystal Reflection Collimation



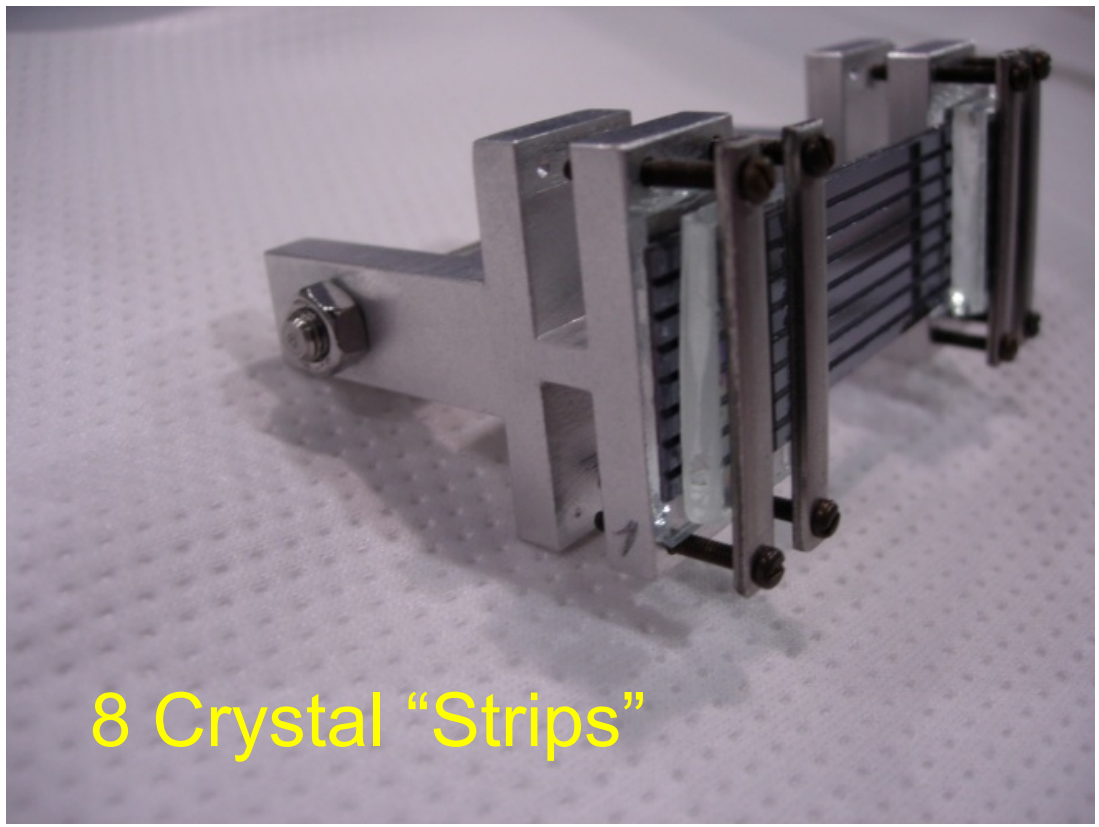
The concept of multiple VR



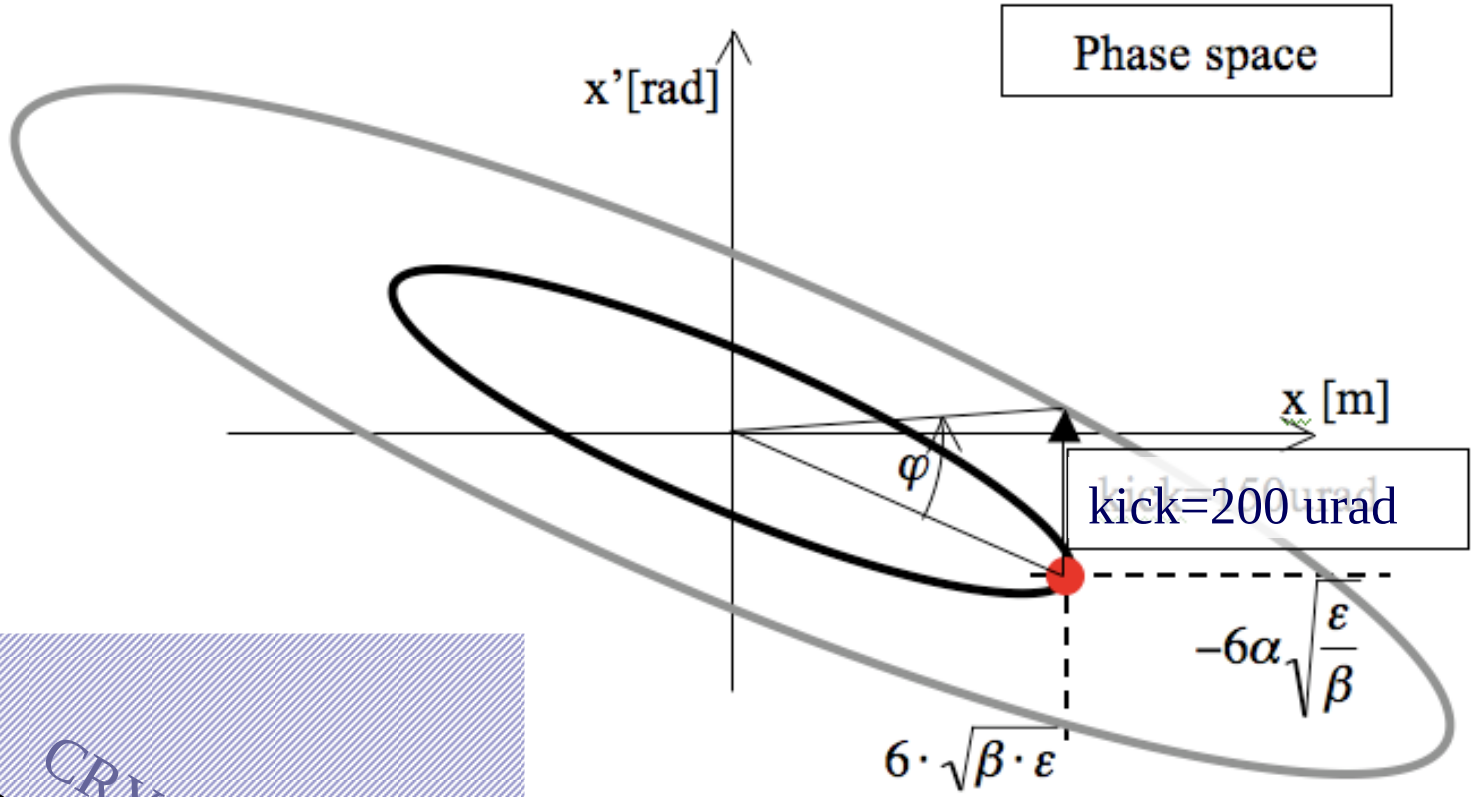
Repeated VRs in an array of parallel crystals results in larger deflection, *e.g.* at *E*=1 TeV:

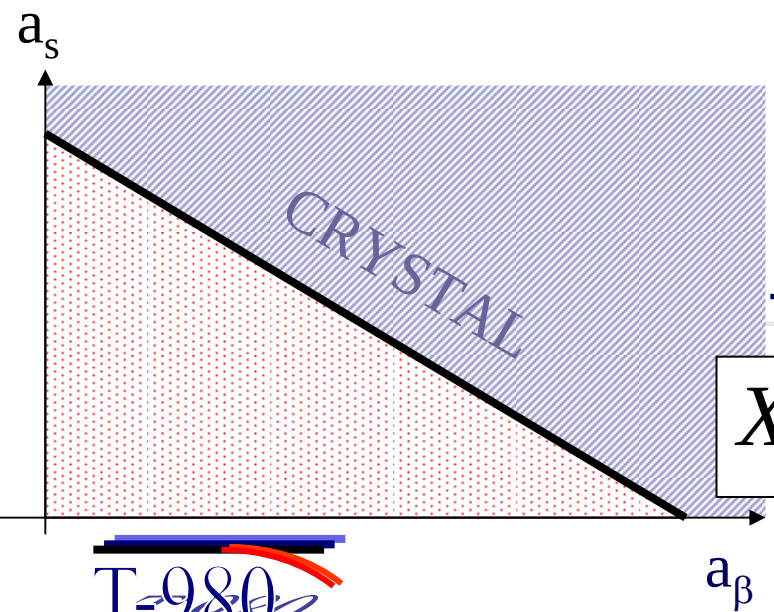
$$One\ crystal \quad \theta_{VR} = 8\,\mu rad;\ \theta_{bend} = 200\,\mu rad$$

$$8\ crystals \quad \theta_{VR} = 8 \times 8 = 64\,\mu rad$$



Which Particles Move Onto Crystals?





Taking synchrotron motion in account:

$$X_{co} + \sigma_x \cdot a_\beta + D \cdot \sigma_p \cdot a_S = X_{crystal}$$

T-980

How Halo Particles Move Onto The Crystal

- Four diffusion processes:
  - Vacuum and transverse noise ~4 nm/√turn
  - RF noise ~12 nm/√turn (Hor) and ~1 nm/√turn (Vert)
  - Beam-beam/NL diffusion ~10-40 nm/√turn
  - (abort gap DC beam only) TEL ~7 μm/turn

  …compare with:
  - 5 mm amorphous Si ~200 μm/√turn
  - 5 mm W primary target ~1.2 mm/√turn
- Two orbit processes:
  - Transverse orbit oscillations ~20 μm, ~15 Hz=3000 turns
  - Synchrotron motion near RF bucket
    ~1 mm (Hor) and ~70 μm (Vert) at ~35 Hz = 1300 turns

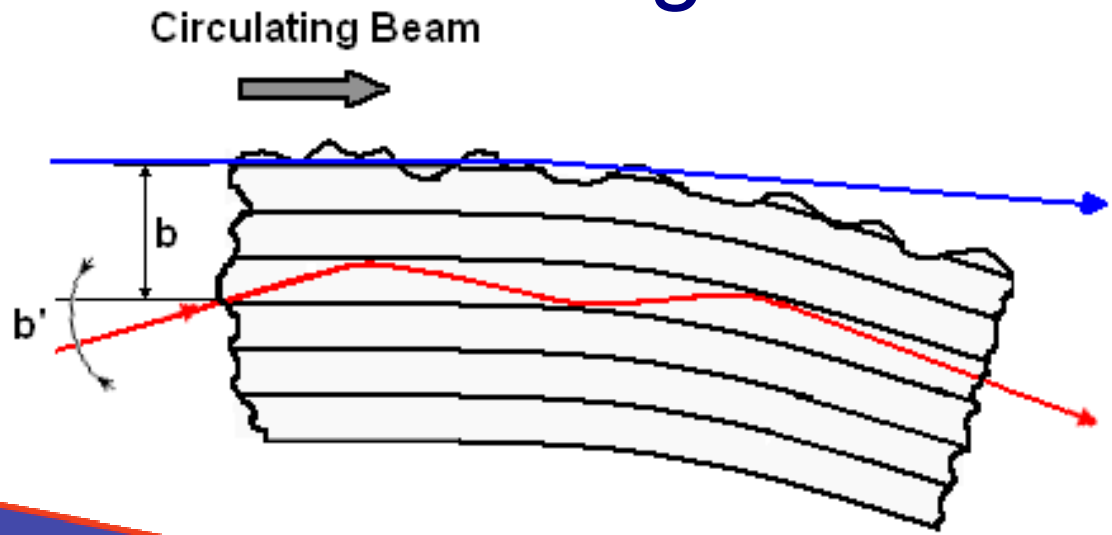
Thus, range of "impact parameters " (depth) of 0.3-30 μm

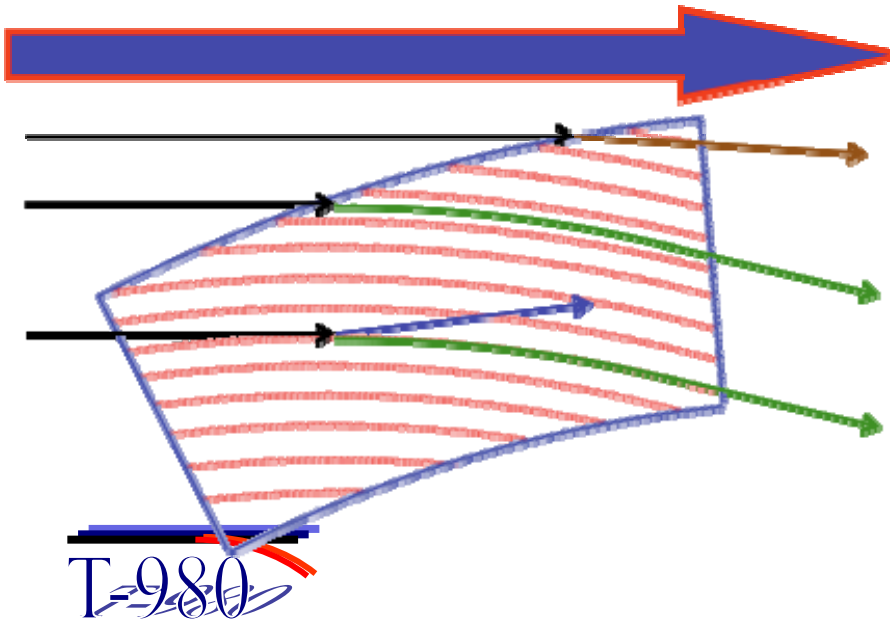
…That Makes Crystal Phenomena in Rings Very Different From Single-Pass

Crystal Surface Phenomena:

1.Surface Roughness:

~100 nm





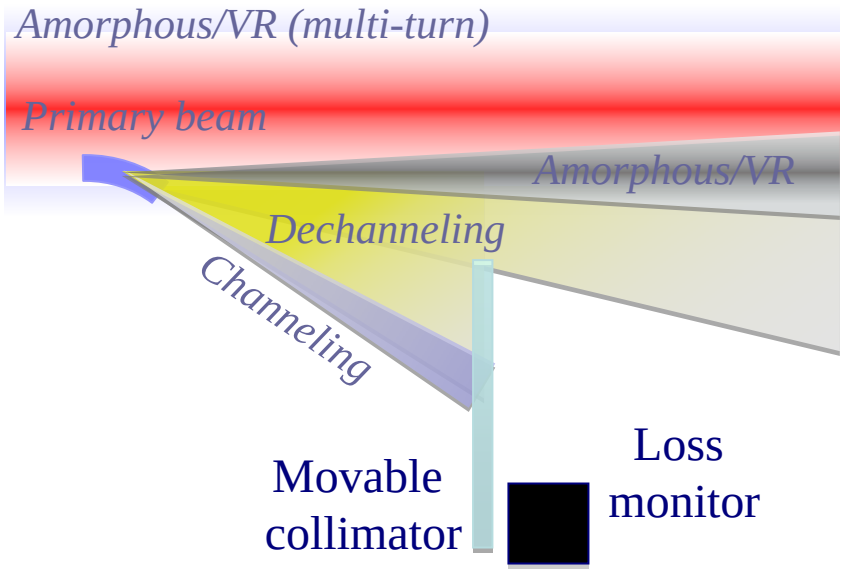
2.Miscut Angle: **~120 µrad**

In the crystal angular scan over the bending angle region of 410 µrad, **there is always an impact parameter region where the particles are channeled with a reduced deflection angle**.

Hence, Because Of These Differences, *The Experiment (T980)*

- One Horizontal O-shaped Crystal
- One Vertical Multi-Strip Crystal
- Both These Crystals At Once

Collimator Scans of Crystal Extracted Beams



- Move collimator into the beam halo
- Vary crystal angle to observe CC/VR beam
- Observe the losses vs collimator *X* position (indicates intensity)

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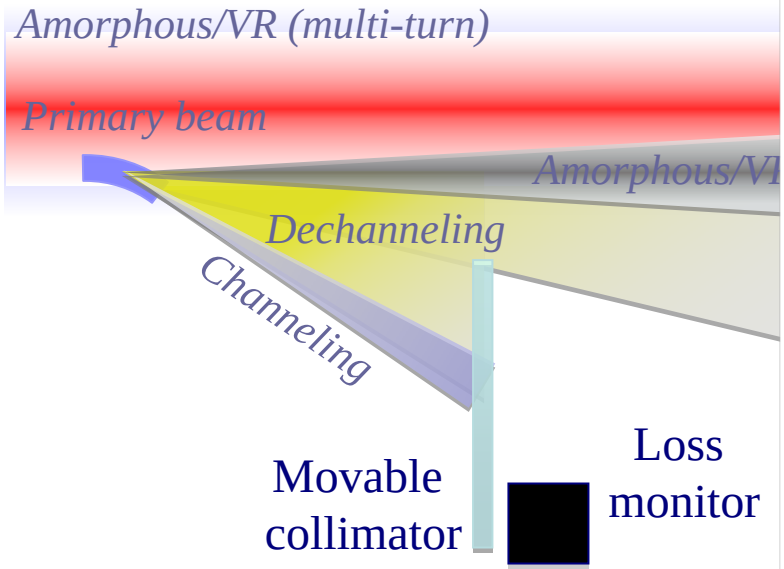

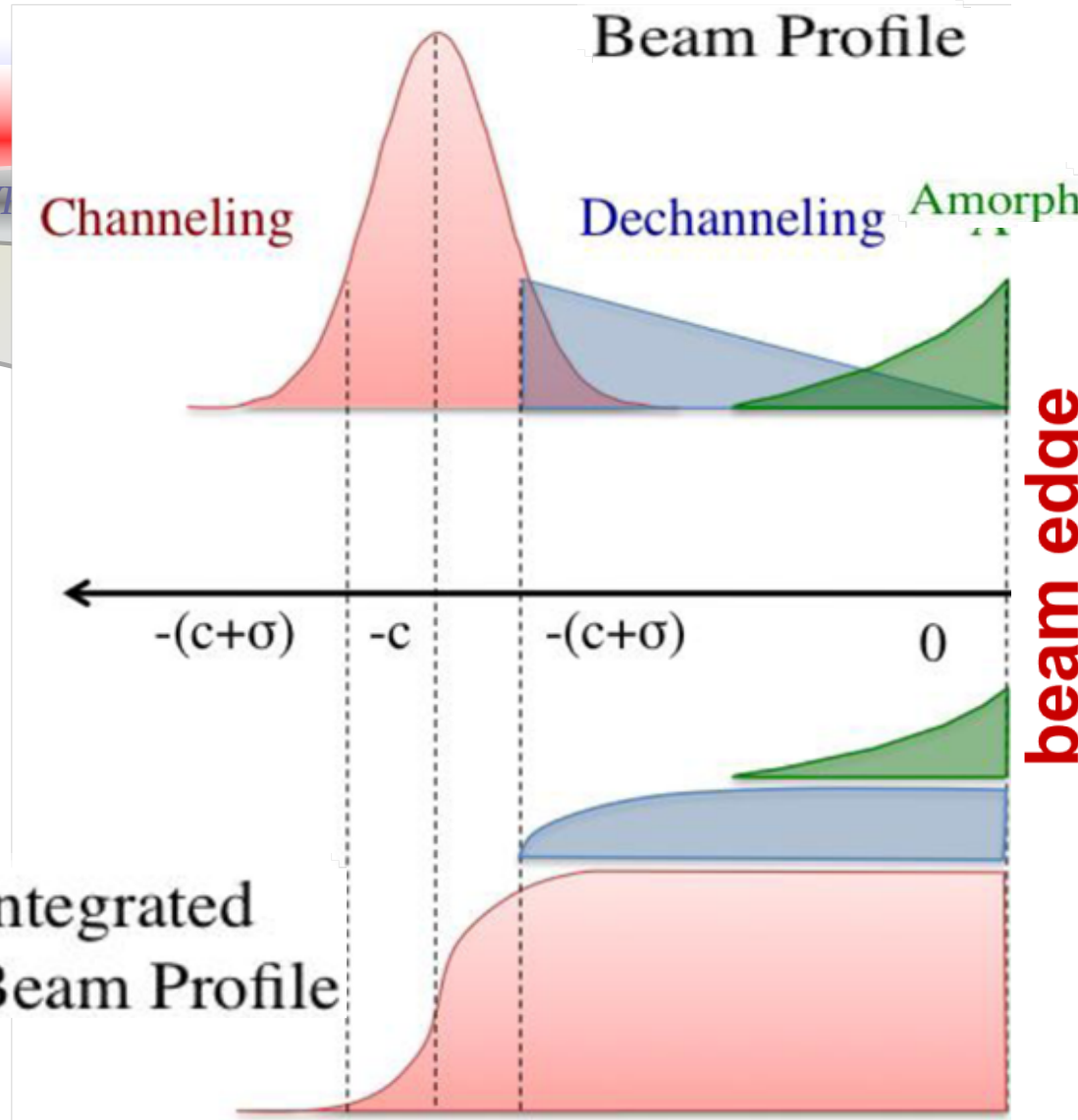

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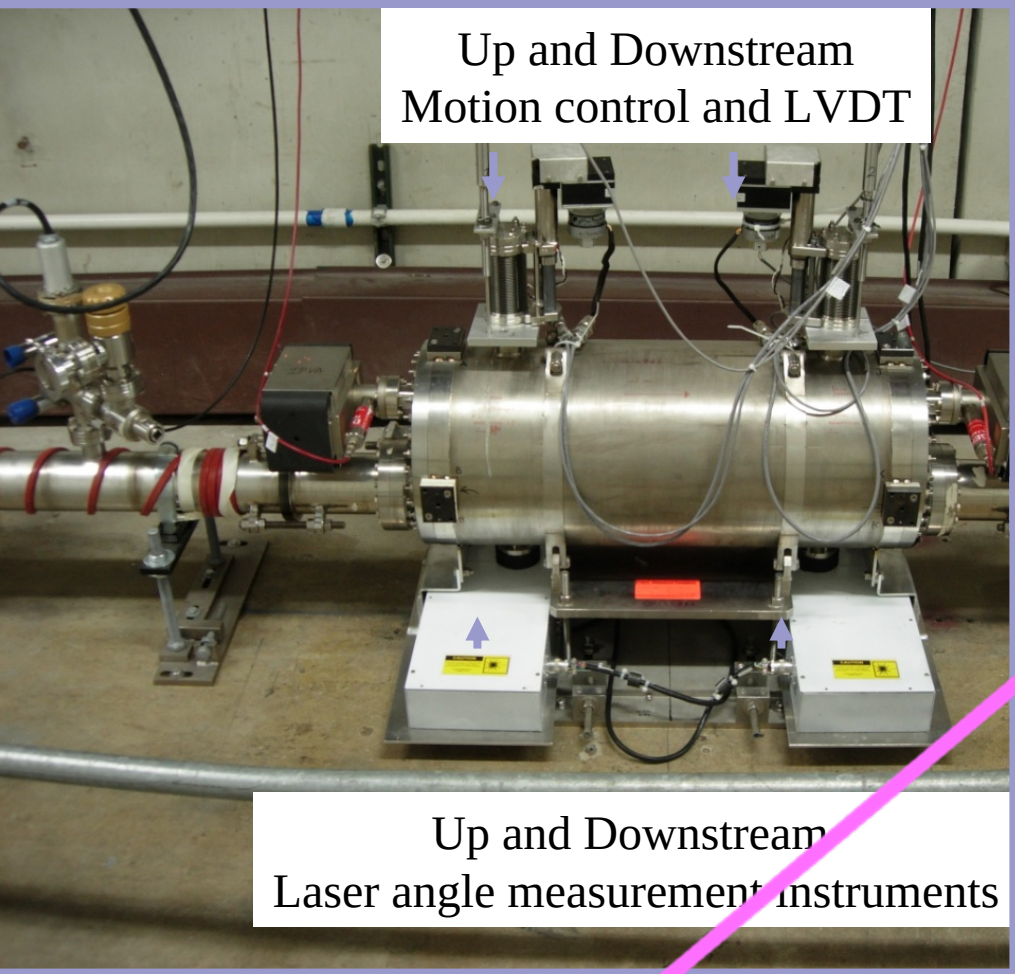
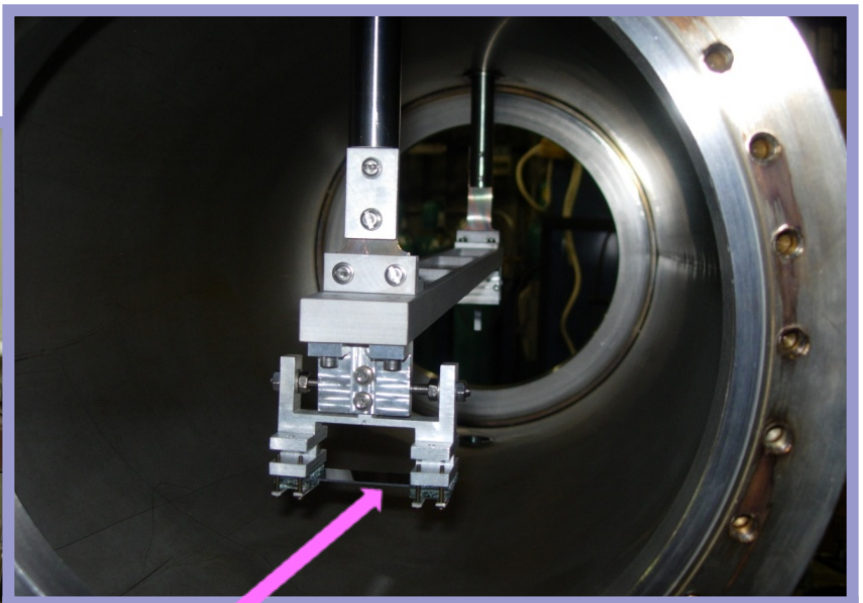
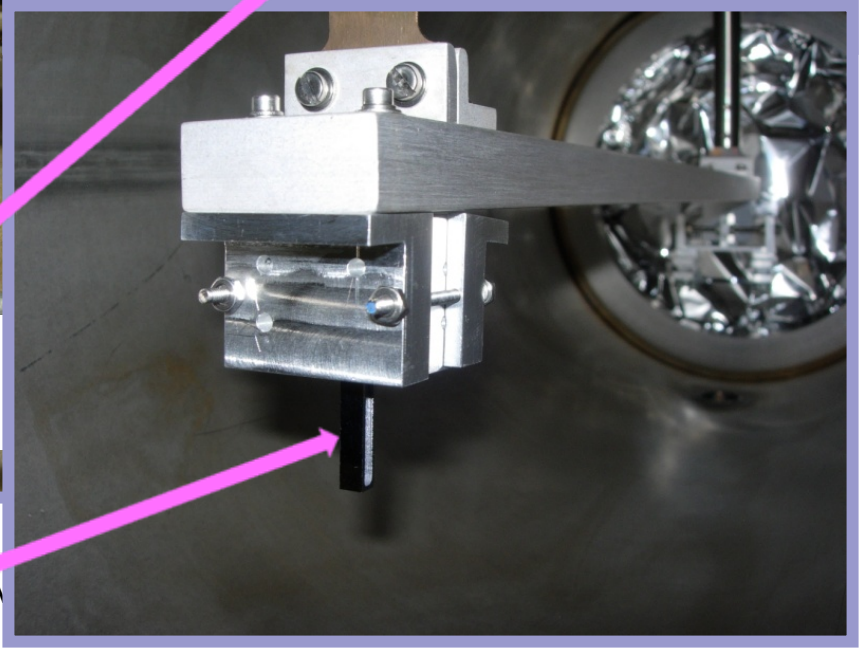
The T980 Experiment Hardware: Goniometers, etc

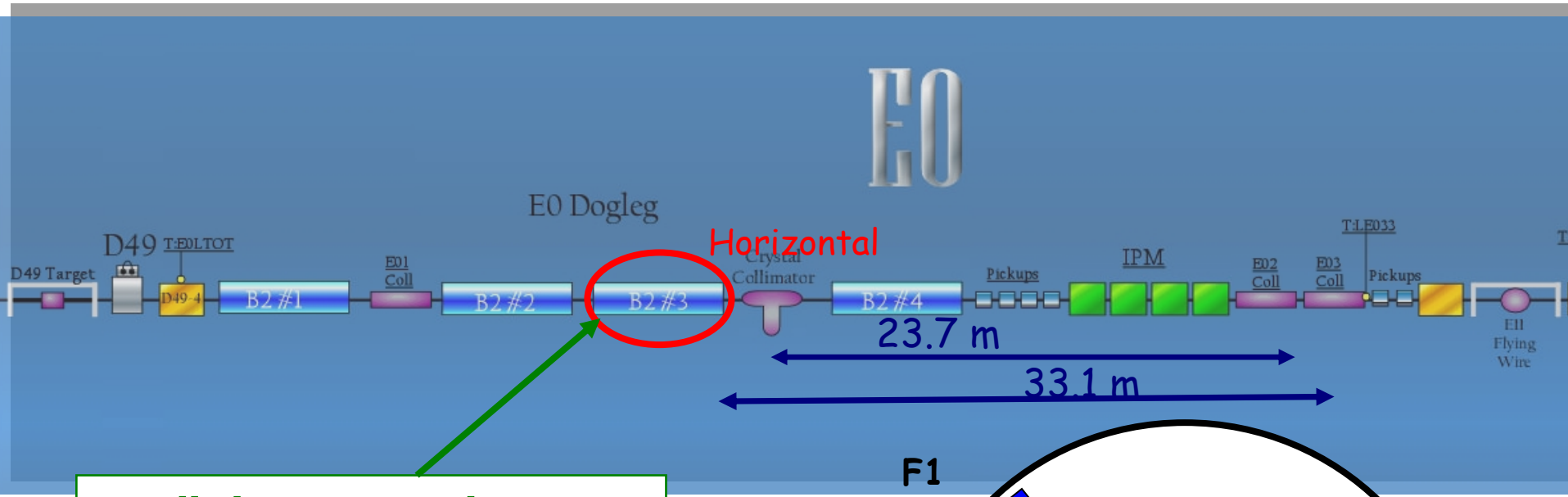






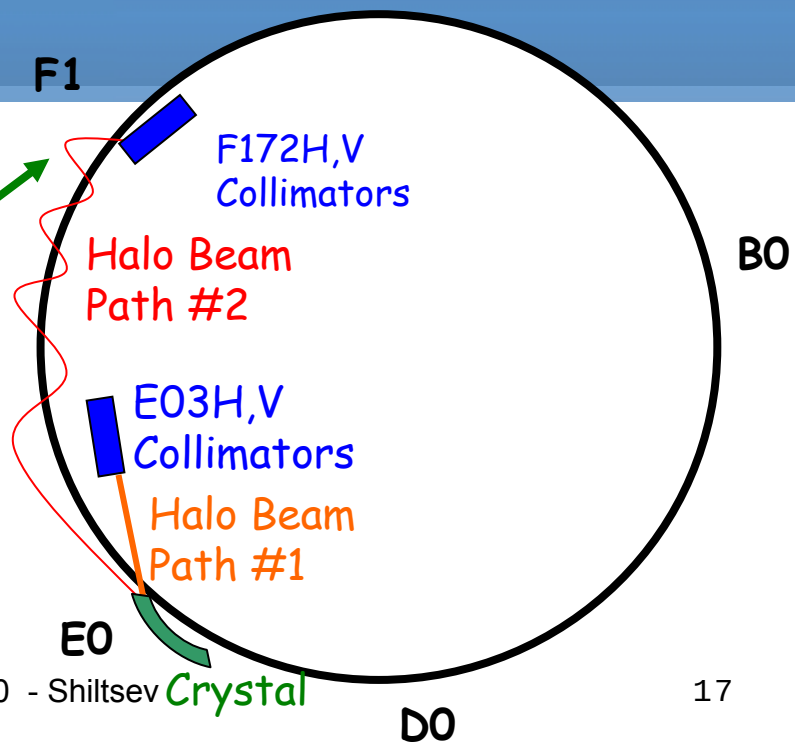
crystals

T980 Setup in Tevatron E0 for 2009-10

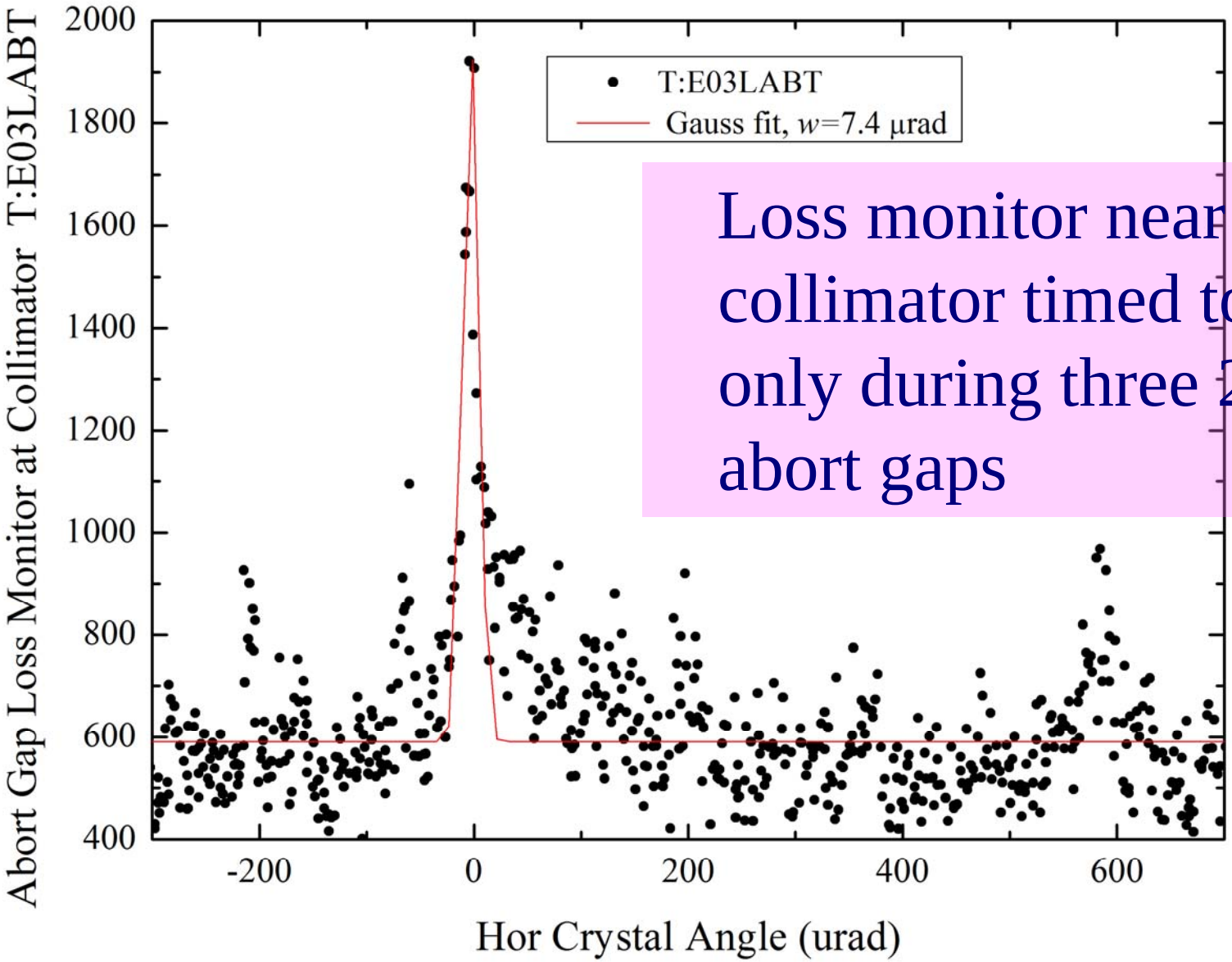


Installed new Vertical goniometer with 2 crystals 4 m upstream of the Horizontal gonoimeter

Also installed new detectors and hardware at F17 to detect volume reflected beam (VR)

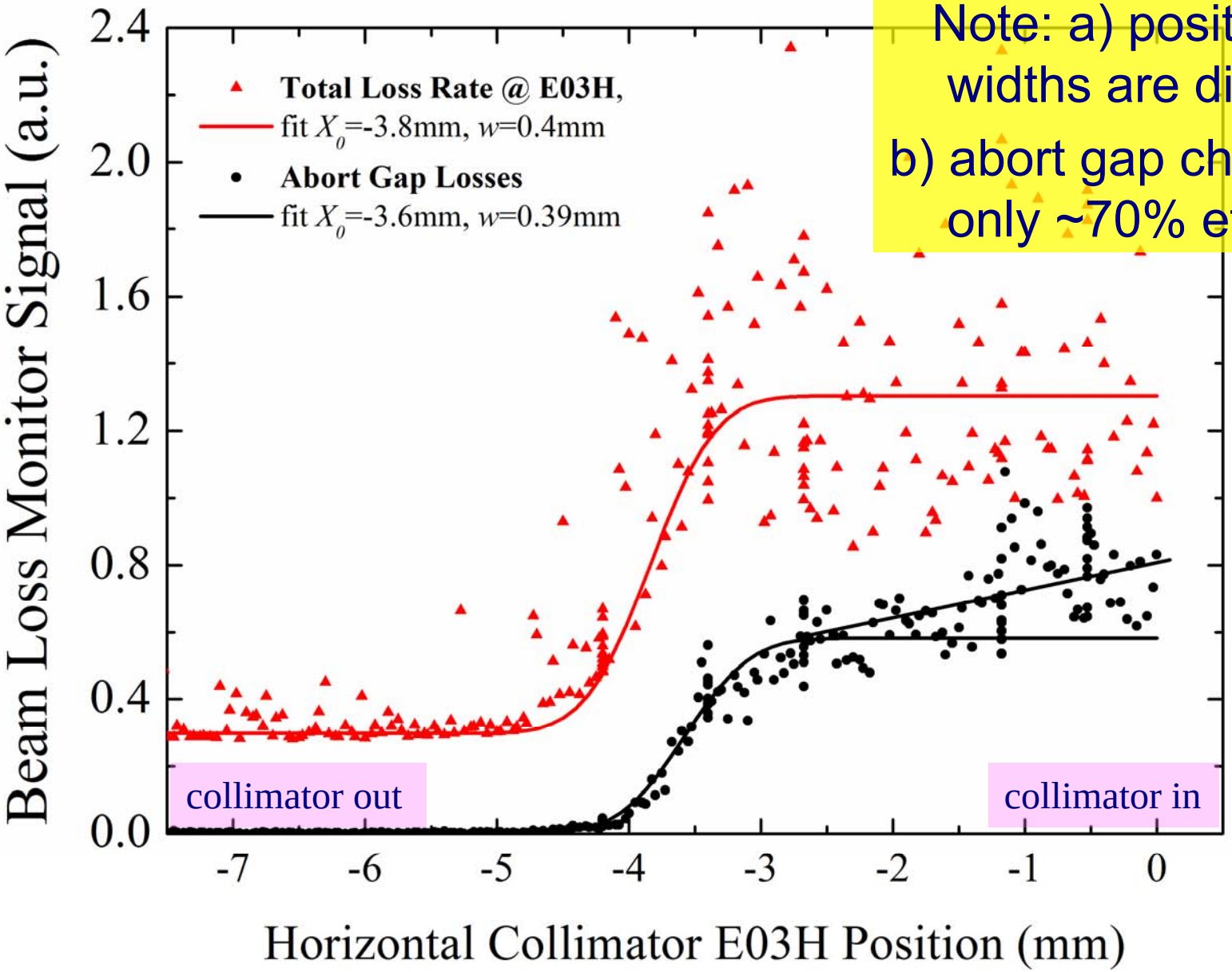


Example of Angle Scan



Loss monitor near E03H collimator timed to count only during three 2.6 us abort gaps

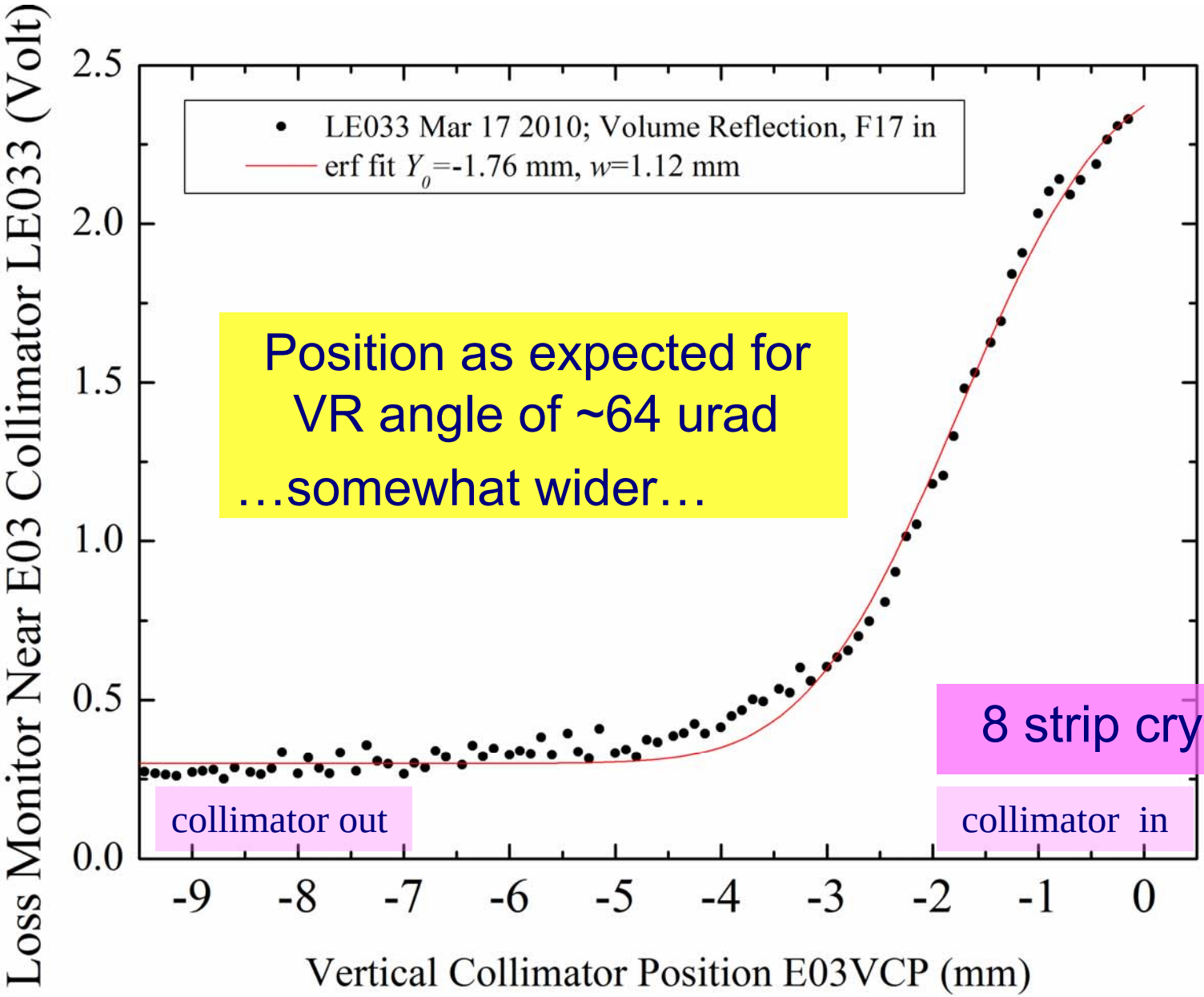
Example of Collimator Scan



Note: a) positions and widths are different

b) abort gap channeling only ~70% efficient

Collimator Scan of Vertical VR Beam



Position as expected for VR angle of ~64 urad

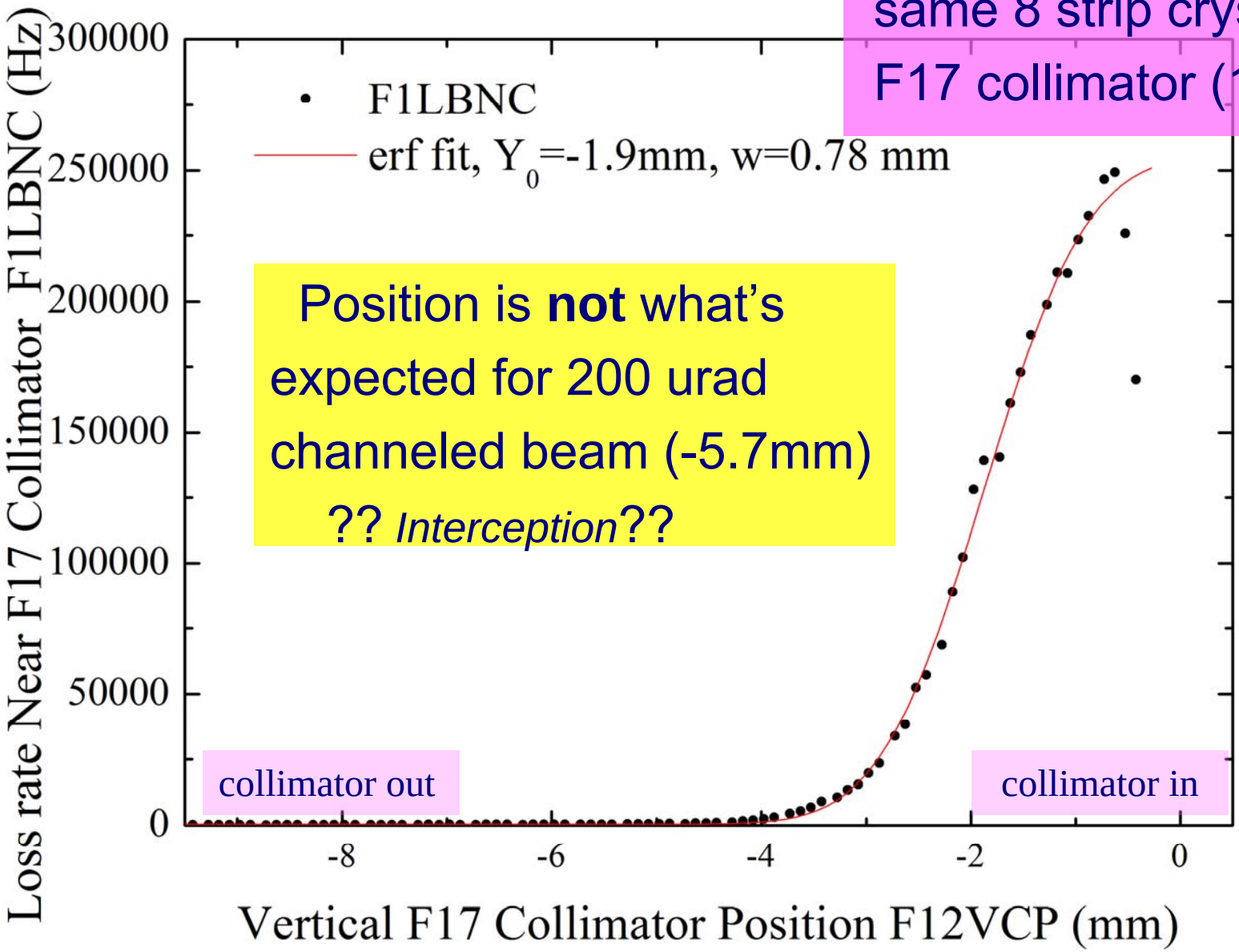
…somewhat wider…

8 strip crystal system

Collimator Scan of Vertical CH Beam

same 8 strip crystal at E0

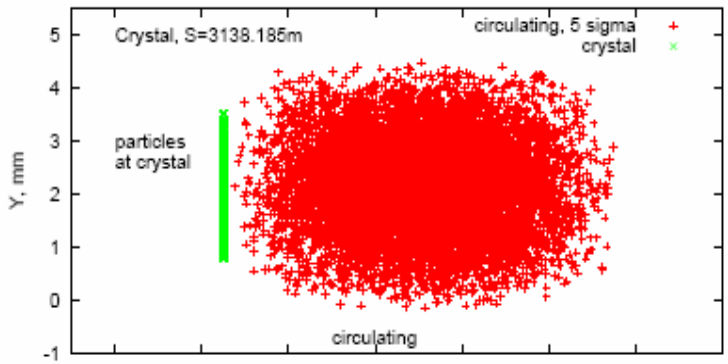
F17 collimator (1km away)

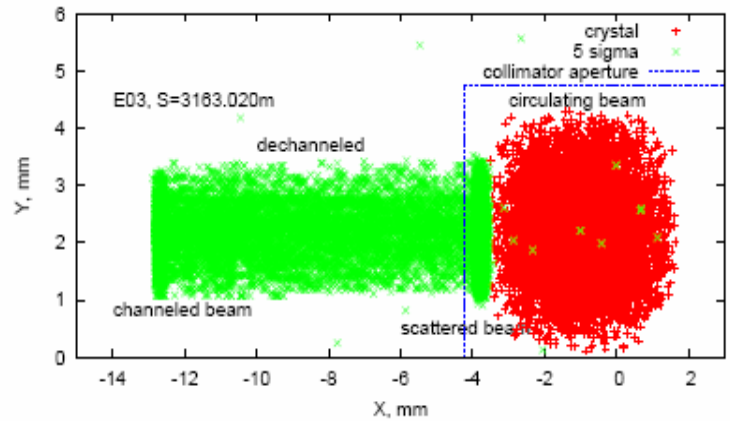


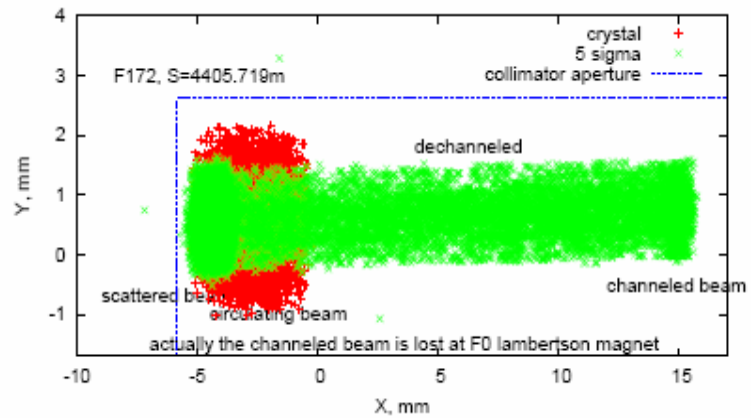
Position is **not** what's expected for 200 urad channeled beam (-5.7mm)

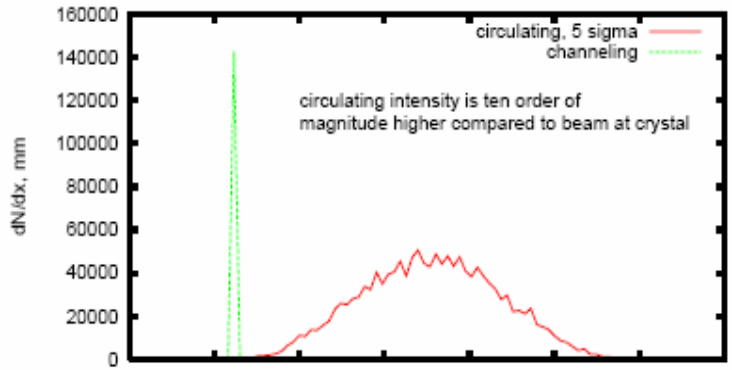
?? *Interception*??

Computer Modeling: Beams @ Collimators

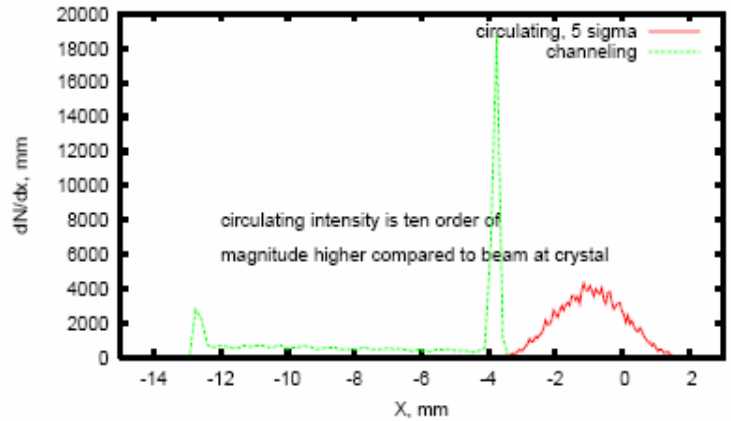




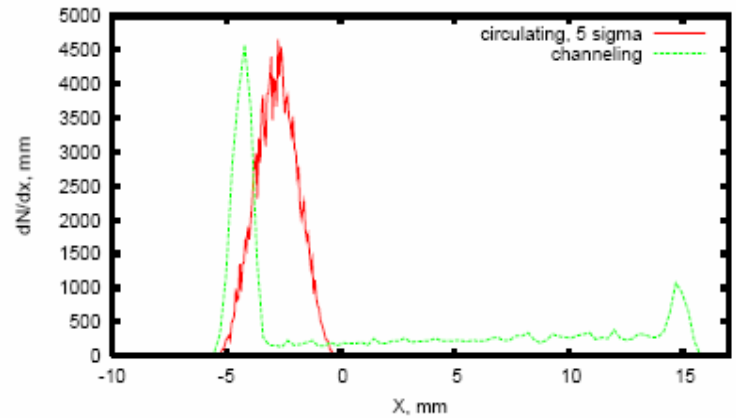




At the Hor Crystal

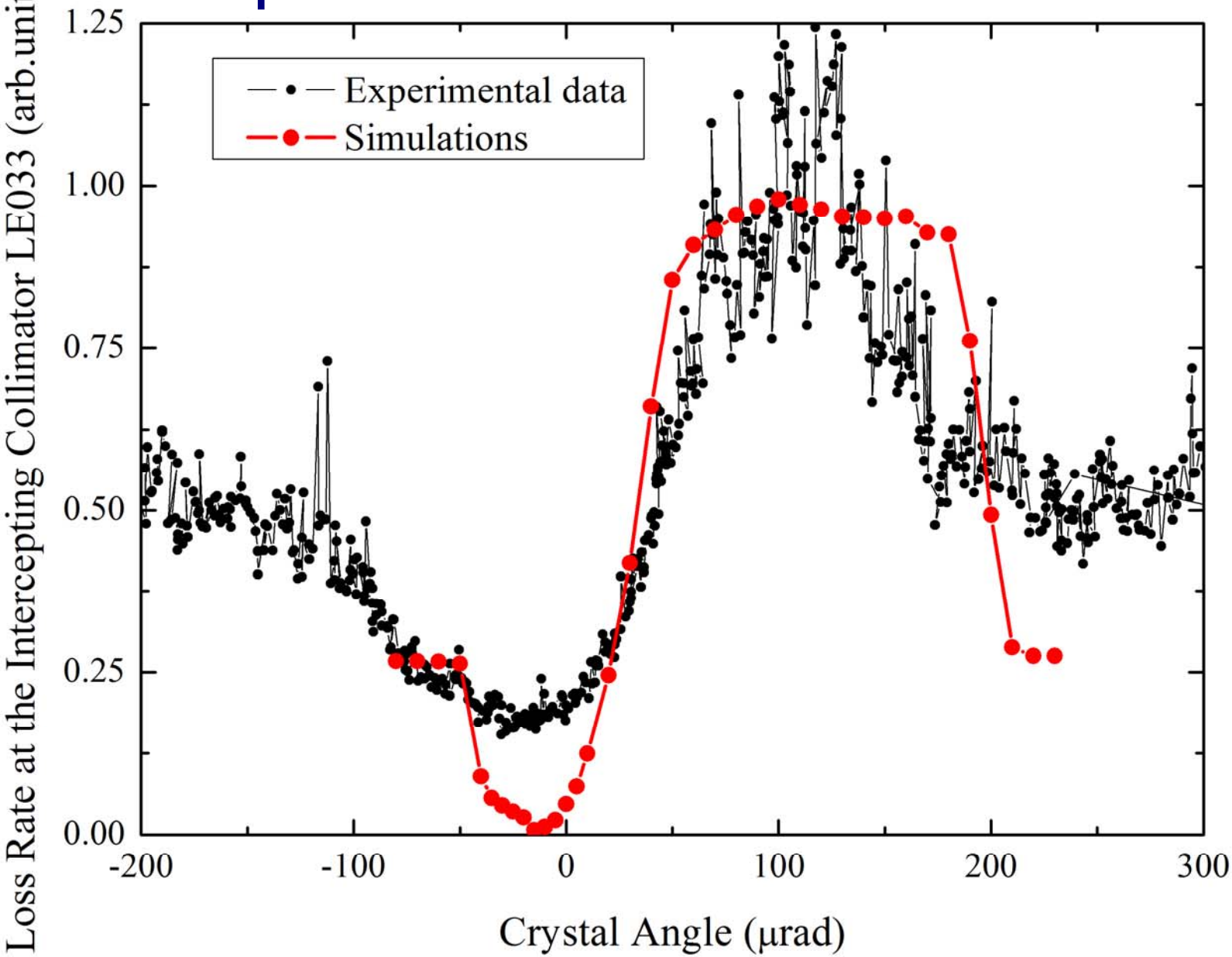


At E03H Collimator

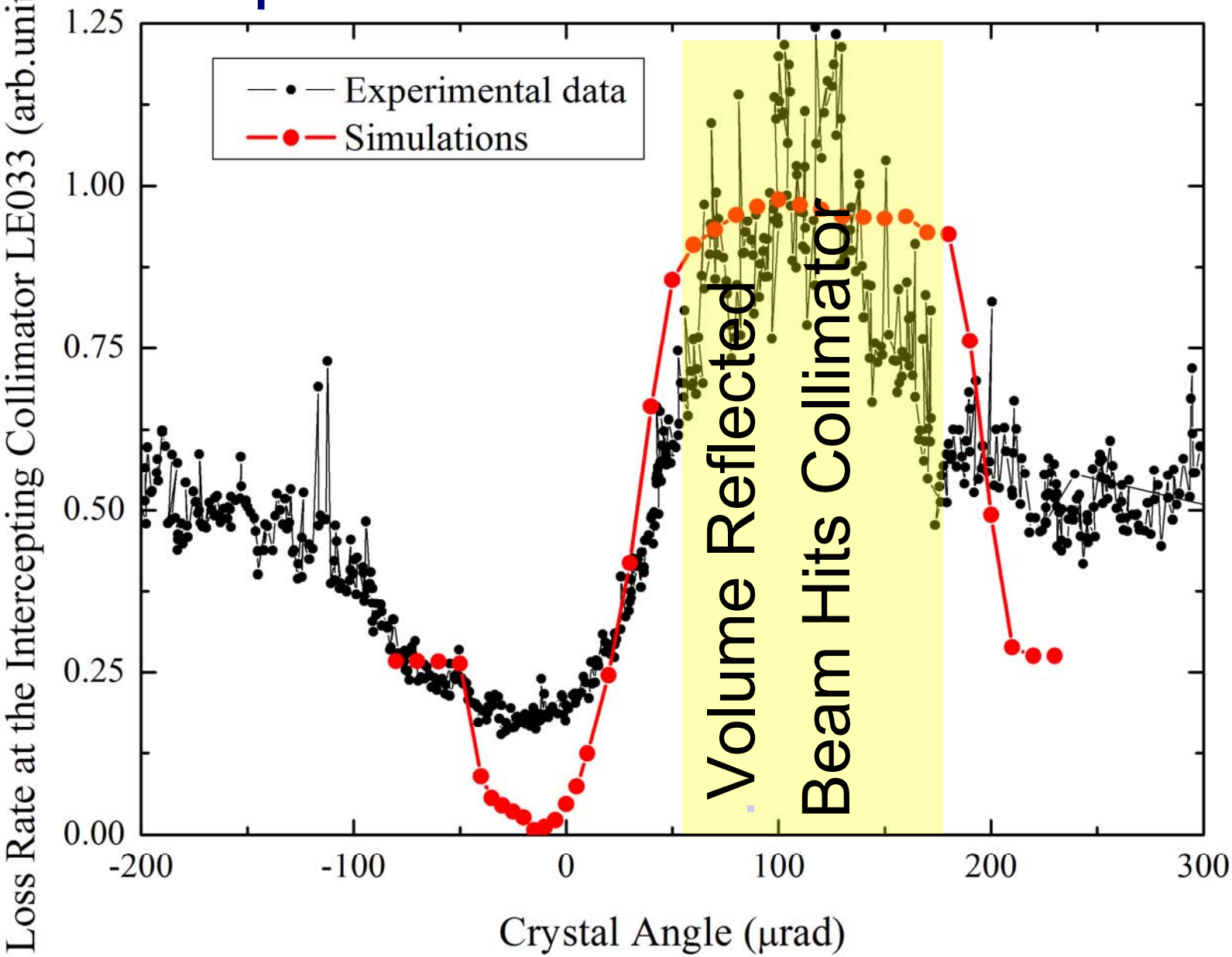


At F172H Collimator

Compare MS Data with Simulations



Compare MS Data with Simulations



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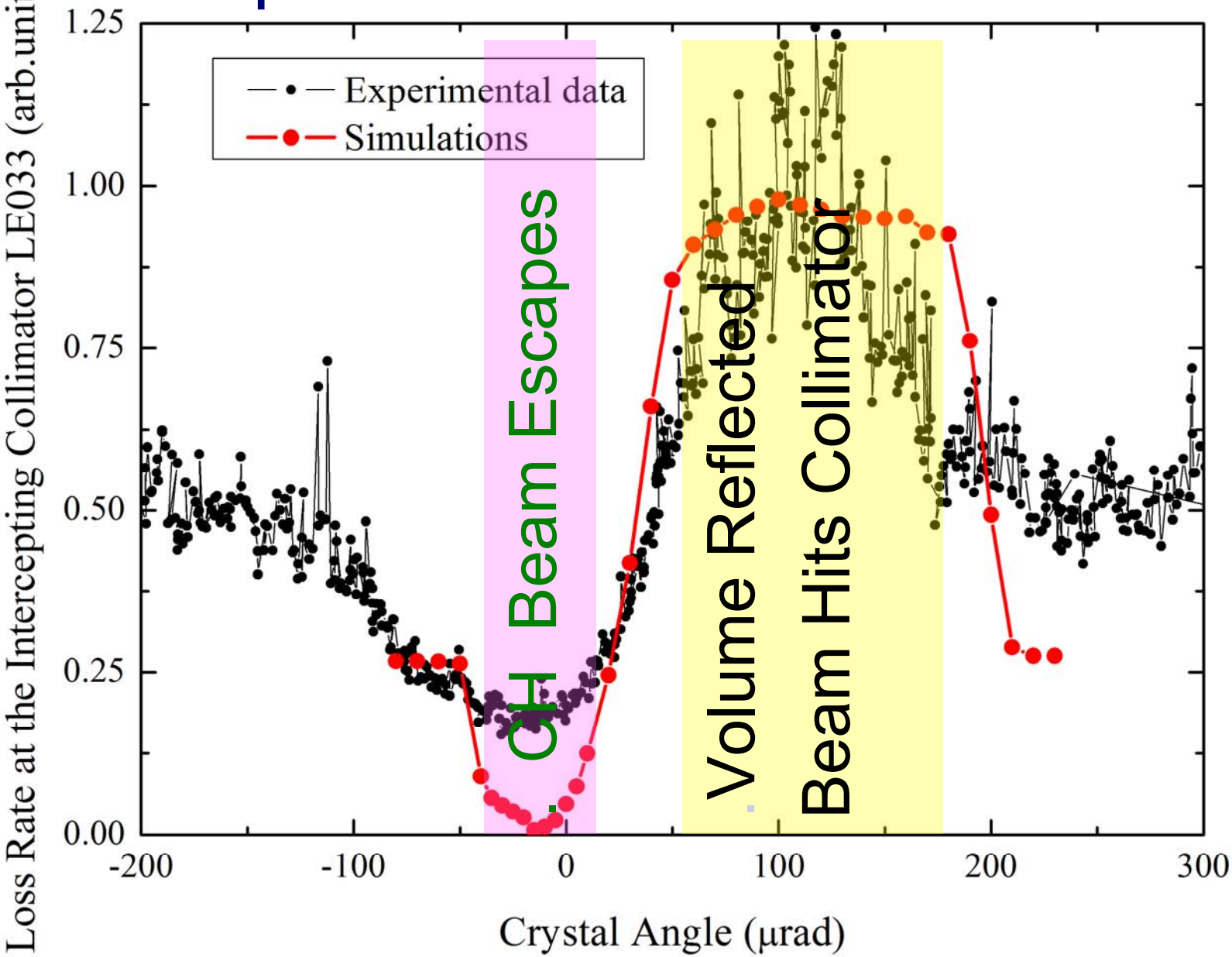
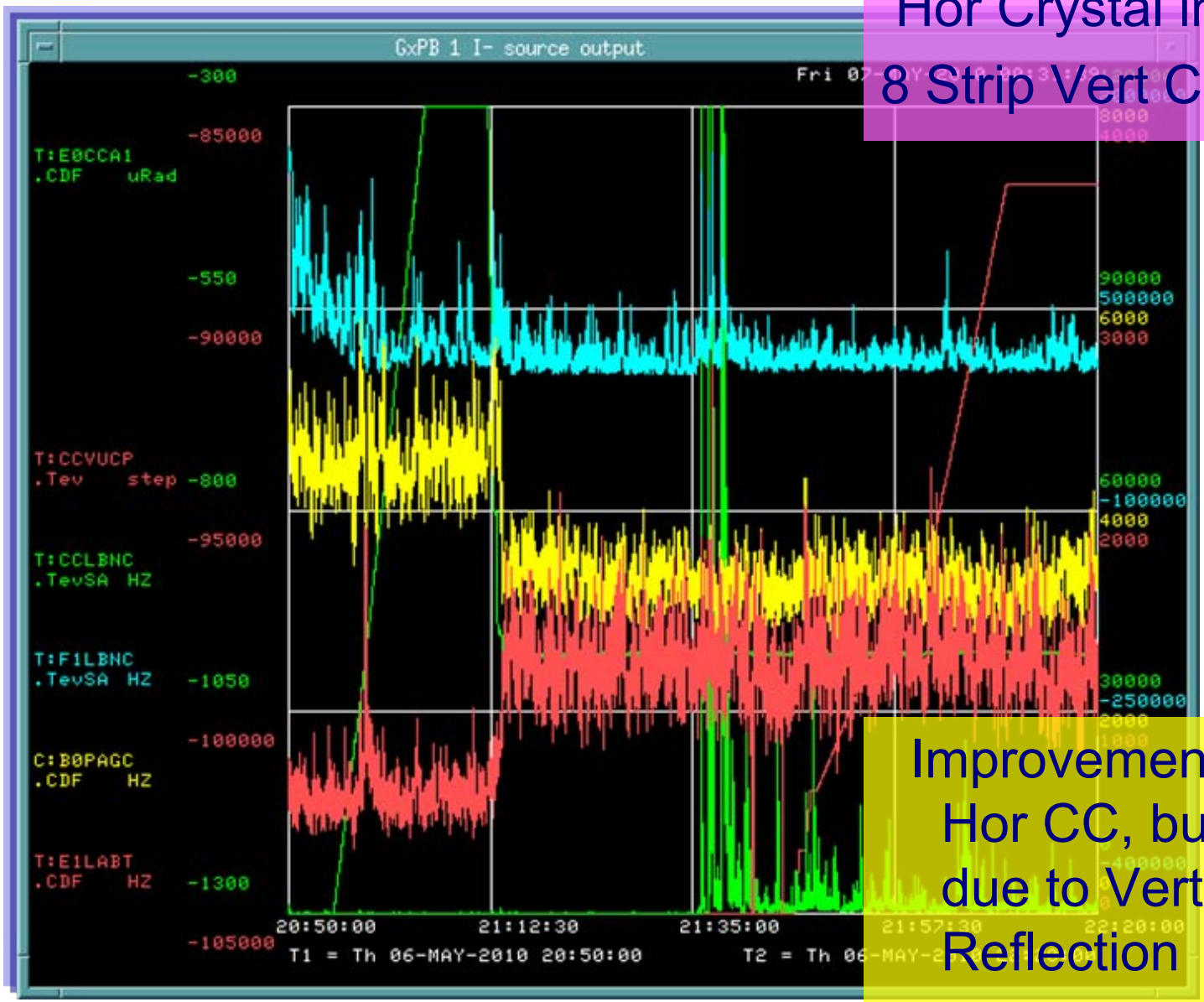


1st Attempt of 2 Plane Crystal Collimation

Hor Crystal in Channeling &
8 Strip Vert Crystal in VR



Improvement seen due to Hor CC, but very little due to Vert MS Volume Reflection

Summary Crystal Collimation in Tevatron

- [x] Crystal collimation has been used during many collider stores in 2009-10
- [x] In 2009, old O-shaped crystal in horizontal goniometer was replaced with new 0.36-mrad O-shaped one (IHEP) with negative 0.12-mrad miscut angle; PLUS, new vertical push-pull goniometer installed 4-m upstream, housing two crystals: 8-strip (IHEP) and old O-shaped ones → therefore, we now have crystals for BOTH planes
- [x] Instrumentation added: eg scintillation telescopes installed at E0 and F17
- [x] A successful fast/automatic insertion of the crystals has been achieved.
- [x] Success in using vertical multi-strip crystal: (1) easy to work with; (2) observed both multiple-VR beam at E03 collimator and a channeled beam at F17 collimator; (3) decent agreement with simulations.
- [x] A reduction of ring losses was reproducibly observed along with local loss effects on the collimator due to crystal channeling.
- [x] First ever attempts of 2 plane crystal collimation … (modest results so far)
- [ ] Quantitative discrepancies btw simulations/expectations and observations

T-980

New Hardware and Plans (2010-11)

- In summer 2010 shutdown, old O-shaped crystal in vertical goniometer will be replaced with new Quasi-Mosaic crystal (PNPI), and 8-strip IHEP crystal will be replaced with advanced 16-strip crystal (INFN, Ferrara), keeping a possibility to alternate them remotely.
- High-resolution pixel telescopes will be installed in front of E03 and F17 collimators to measure channeled and VR beam profiles at those locations with resolution ~5 μm.
- Broad experimental program with this enhanced system is planned starting September 2010 through October 2011 for thorough study of two-plane crystal collimation efficiency in EOS and full collider stores. It aims at demonstration of improved reproducible beam loss localization in collimation region, reduction of beam losses around the ring, and specifically in the CDF and D0 collider detector regions.

T-980