Fermilab
U.S. DEPARTMENT OF ENERGY | Office of Science

Experience with Crystals at Fermilab

Vladimir SHILTSEV (Fermilab)

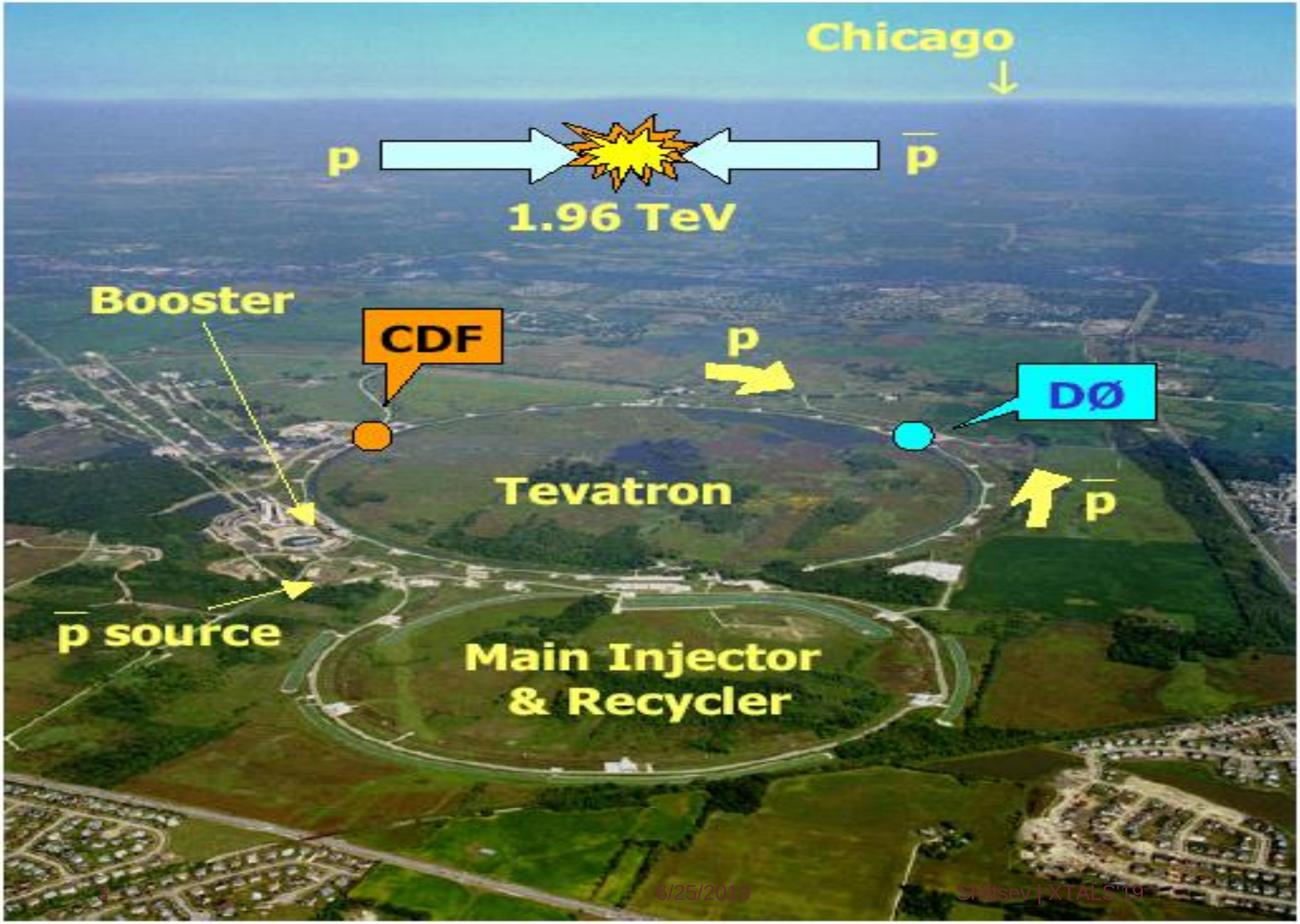
Workshop on Acceleration In Crystals and Nanostructures

June 24-25, 2019 - Fermilab

Past Experience at Fermilab

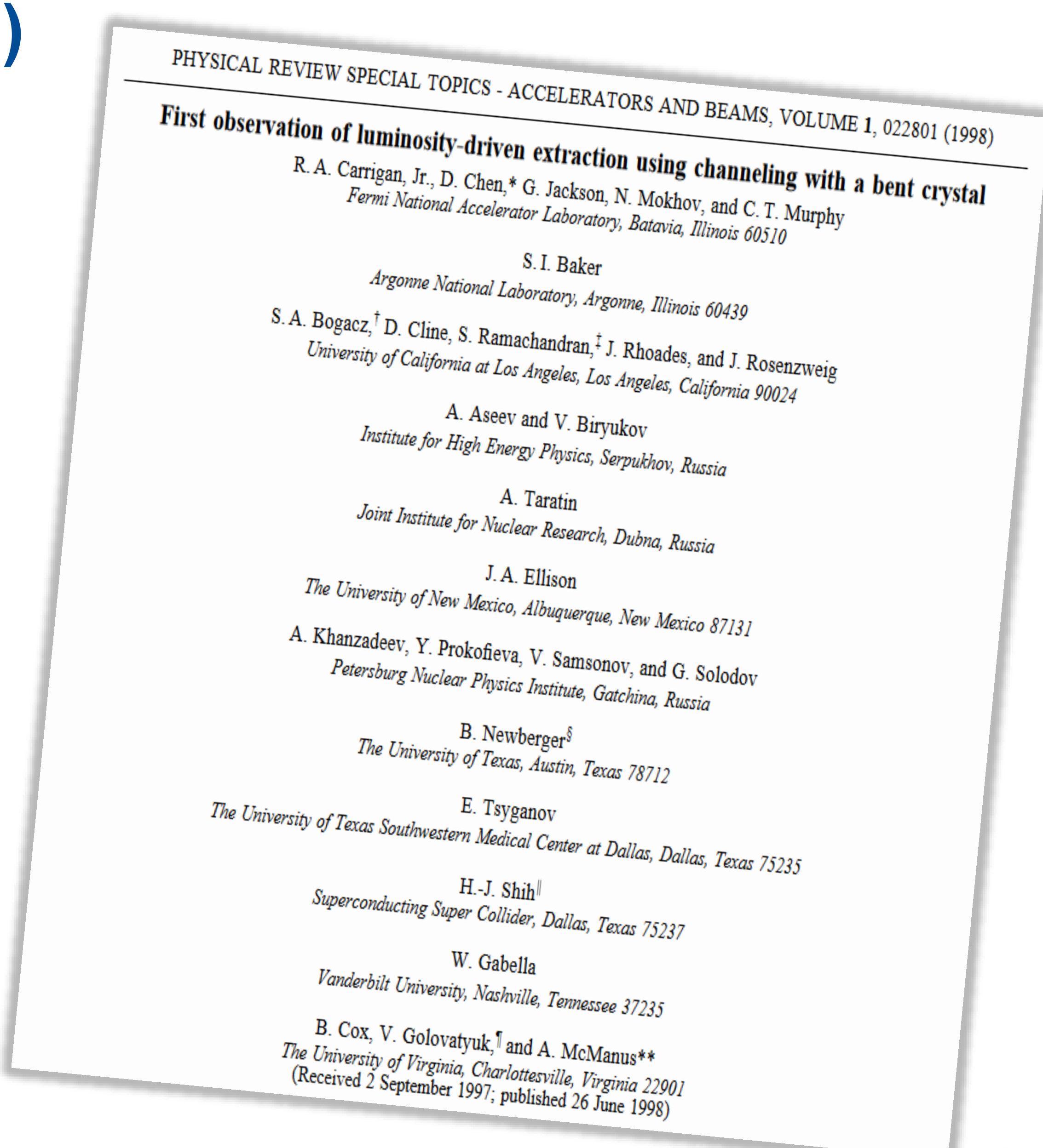
- **Slow extraction (Tevatron Run I):** 1990's
  - R.Carrigan, et al
- **Halo collimation (Tevatron Collider Run II):**
  - N.Mokhov, D.Still, V.Shiltsev, et al.
  - 2004-2011; T980 experiment
- **Channeling experiments at FAST:** 2015-
  - P.Piot, T.Sen, Y.M.Shin, J.Thangaraj, et al.
- **What can be re-used for the new Xtal acceleration R&D:**
  - hardware

Tevatron *p-pbar* Collider Run I (1992-96) and Run II (2001-2011)



#1: 1990's (paper 1)

Luminosity-driven channeling extraction has been observed for the first time using a 900 GeV circulating proton beam at the superconducting Fermilab Tevatron. The extraction efficiency was found to be about 30%. A 150 kHz beam was obtained during luminosity-driven extraction with a tolerable background rate at the collider experiments. A 900 kHz beam was obtained when the background limits were doubled. This is the highest energy at which channeling has been observed


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **1**, 022801 (1998)

First observation of luminosity-driven extraction using channeling with a bent crystal

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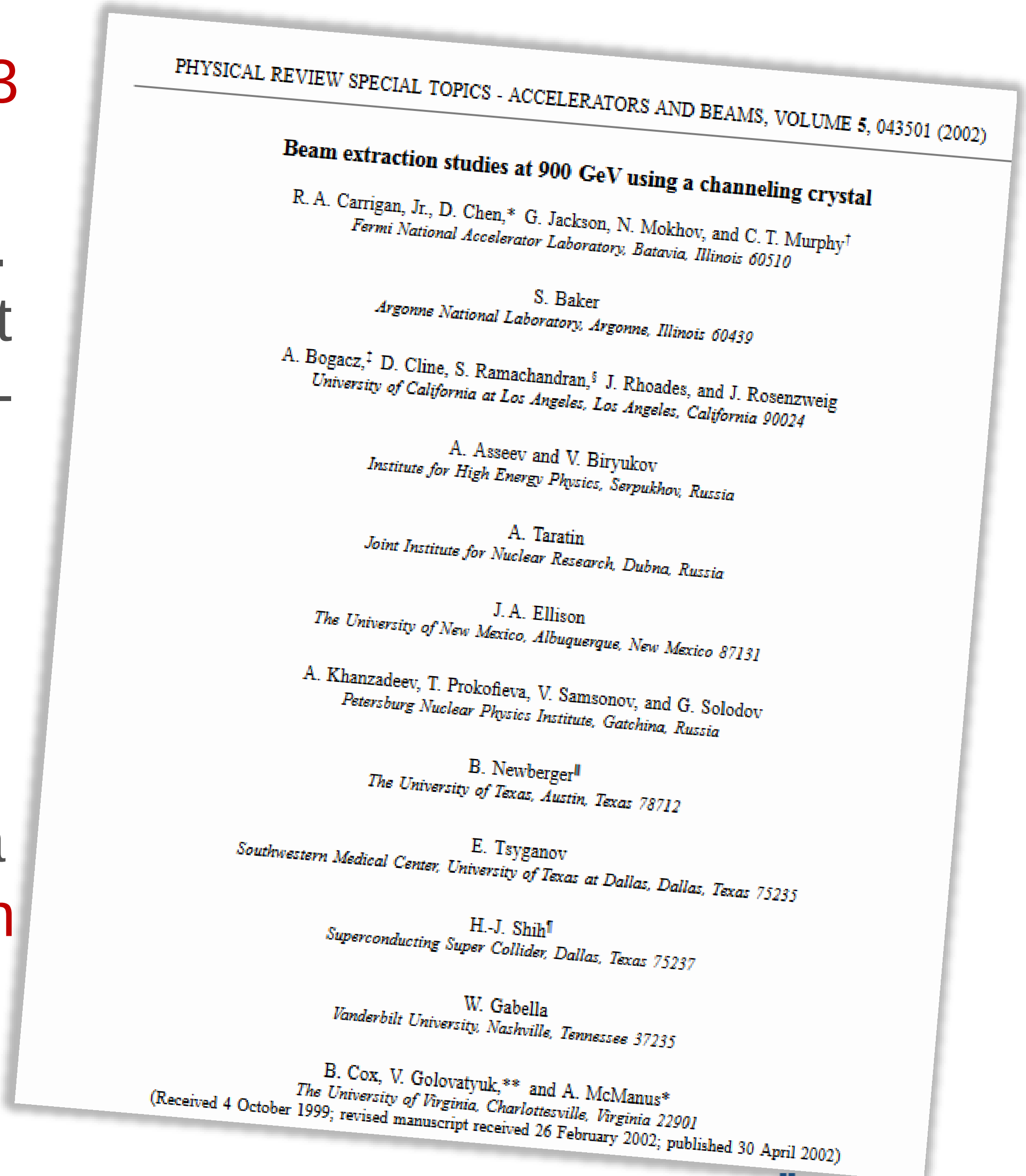
B. Cox, V. Golovatyuk,¶ and A. McManus**
The University of Virginia, Charlottesville, Virginia 22901
(Received 2 September 1997; published 26 June 1998)

Paper #2 (2002)

- experiment Fermilab E853
- The beam extraction efficiency was about 25%. Studies of time dependent effects found that the turn-to-turn structure was governed mainly by accelerator beam dynamics. Based on the results of this experiment, it is feasible to construct a parasitic 5–10 MHz proton beam from the Tevatron collider.


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 5, 043501 (2002)

Beam extraction studies at 900 GeV using a channeling crystal

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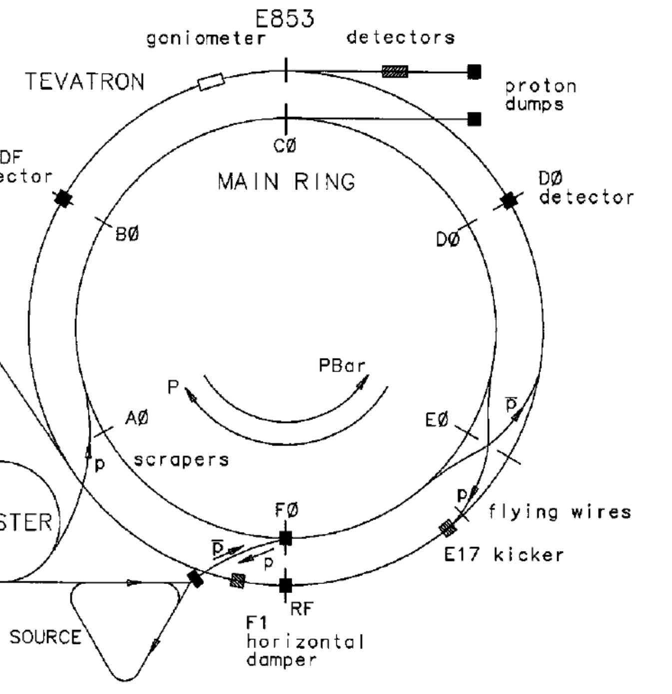
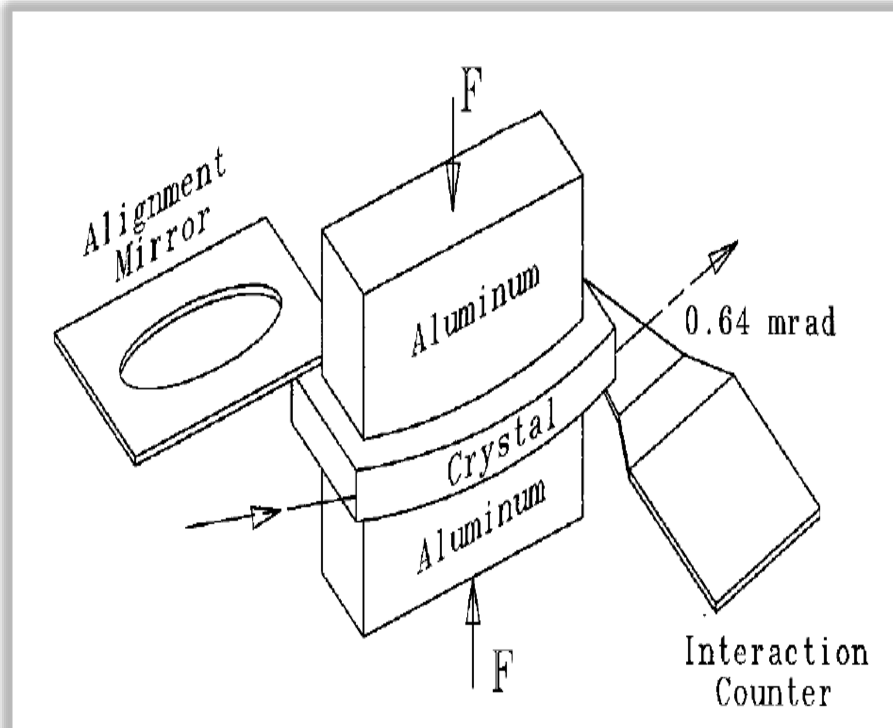
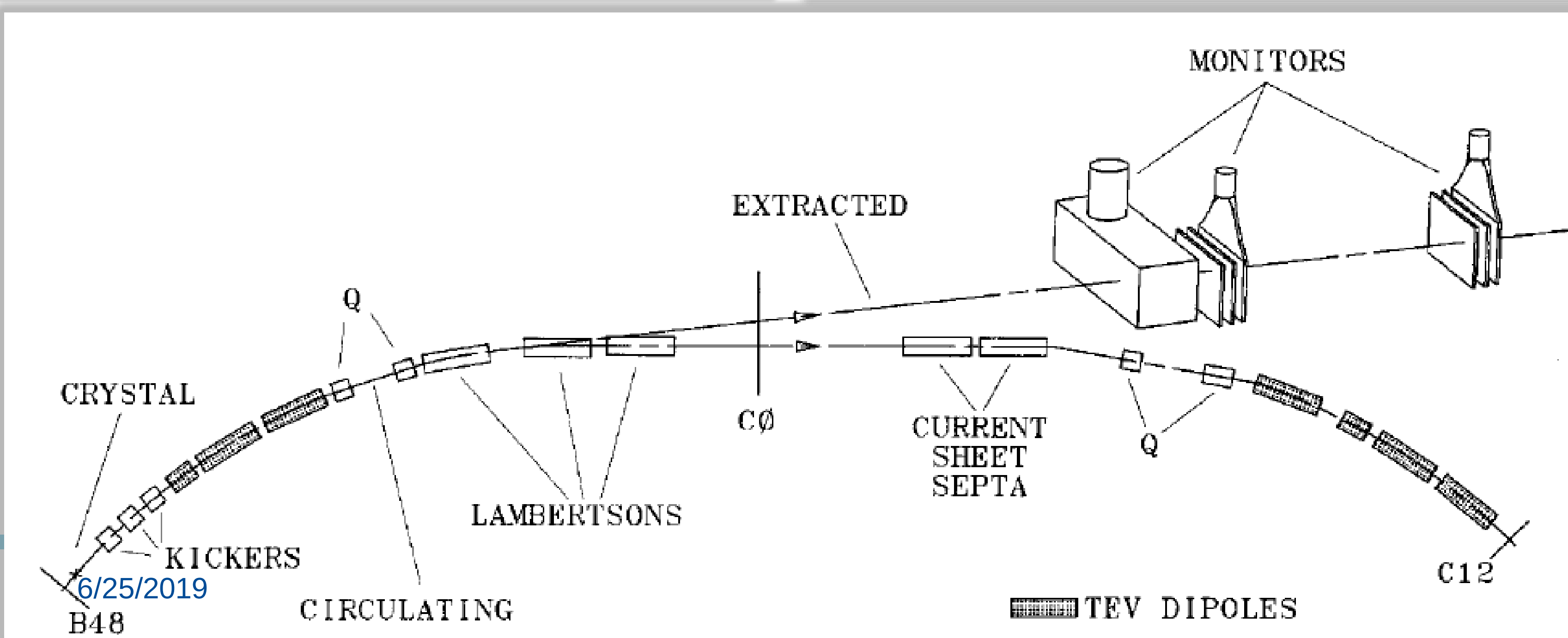
(Received 4 October 1999; revised manuscript received 26 February 2002; published 30 April 2002)

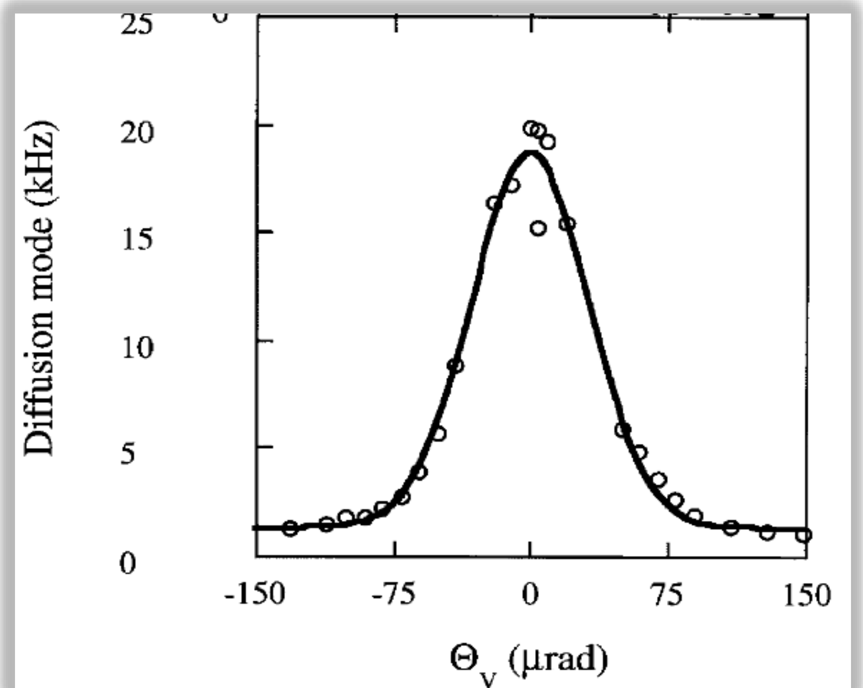
E853


E853
goniometer
detectors
TEVATRON
proton
dumps
CØ
CDF
detector
MAIN RING
DØ
detector
BØ
DØ
extraction
PBar
P
LINAC
AØ
EØ
p
p
scrapers
p
FØ
flying wires
BOOSTER
p
p
E17 kicker
RF
P SOURCE
F1
horizontal
damper

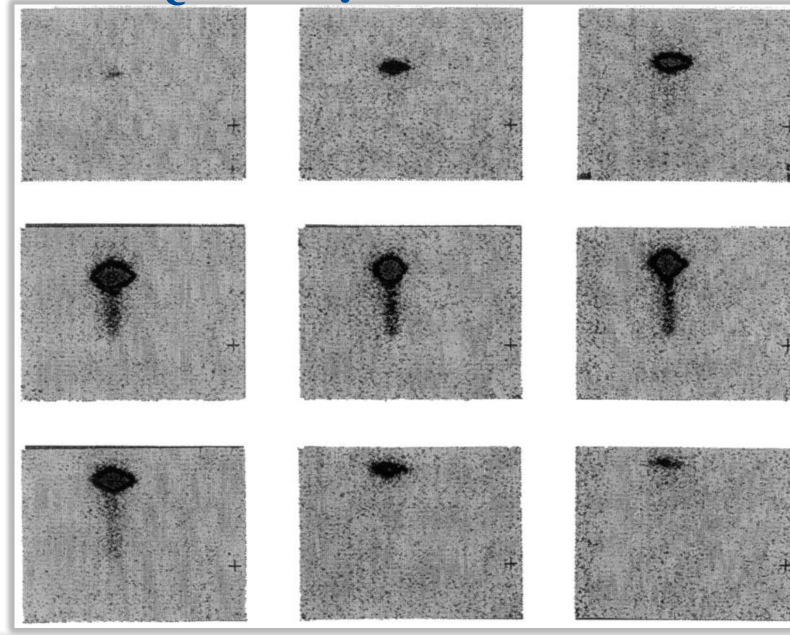

F
Alignment
Mirror
Aluminum
0.64 mrad
Crystal
Aluminum
F
Interaction
Counter

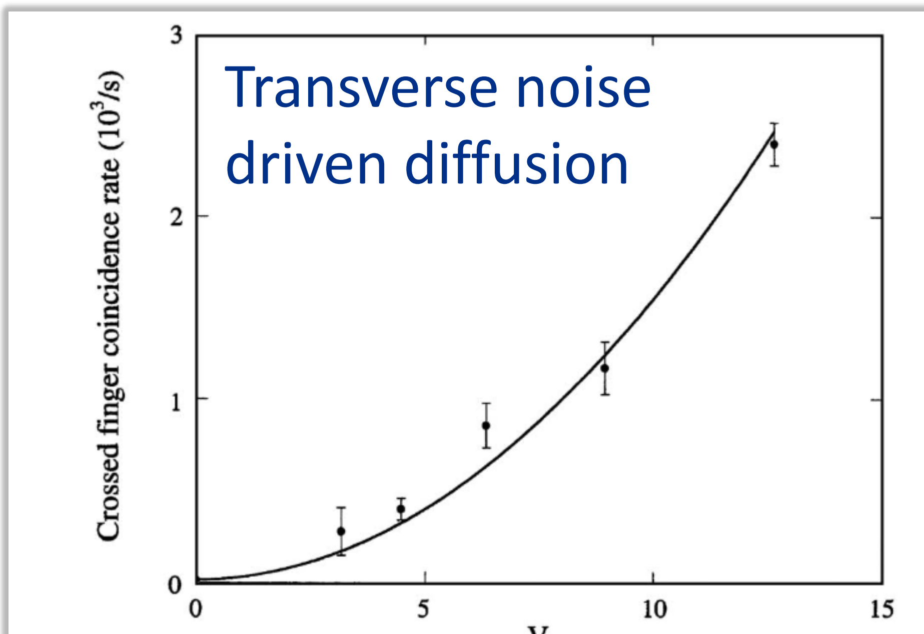

MONITORS
EXTRACTED
Q
CRYSTAL
CØ
CURRENT
SHEET
SEPTA
Q
LAMBERTSONS
KICKERS
C12
B48
CIRCULATING
TEV DIPOLES

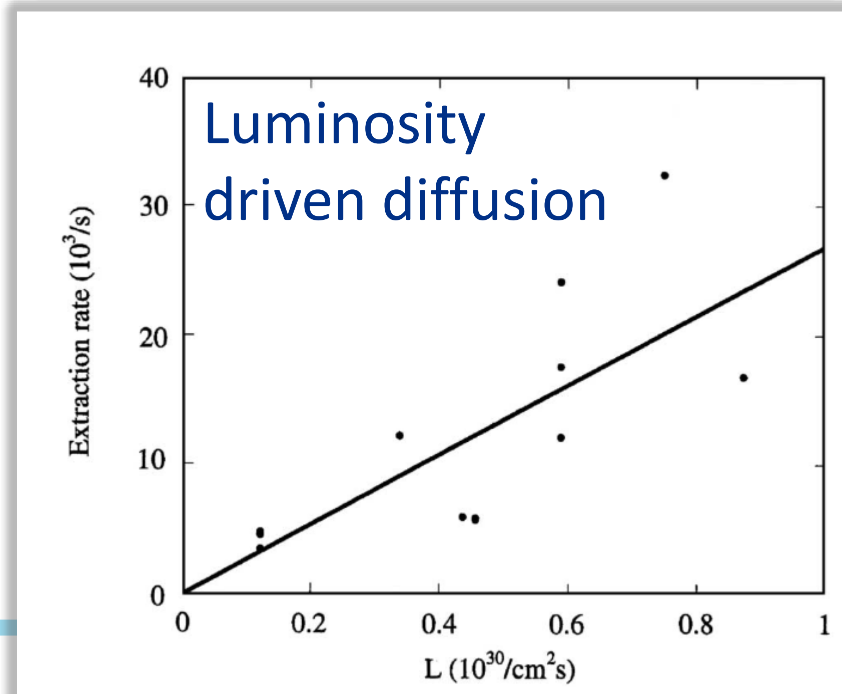
E853 θ_c ~32 μrad at 900 GeV



dechanneling

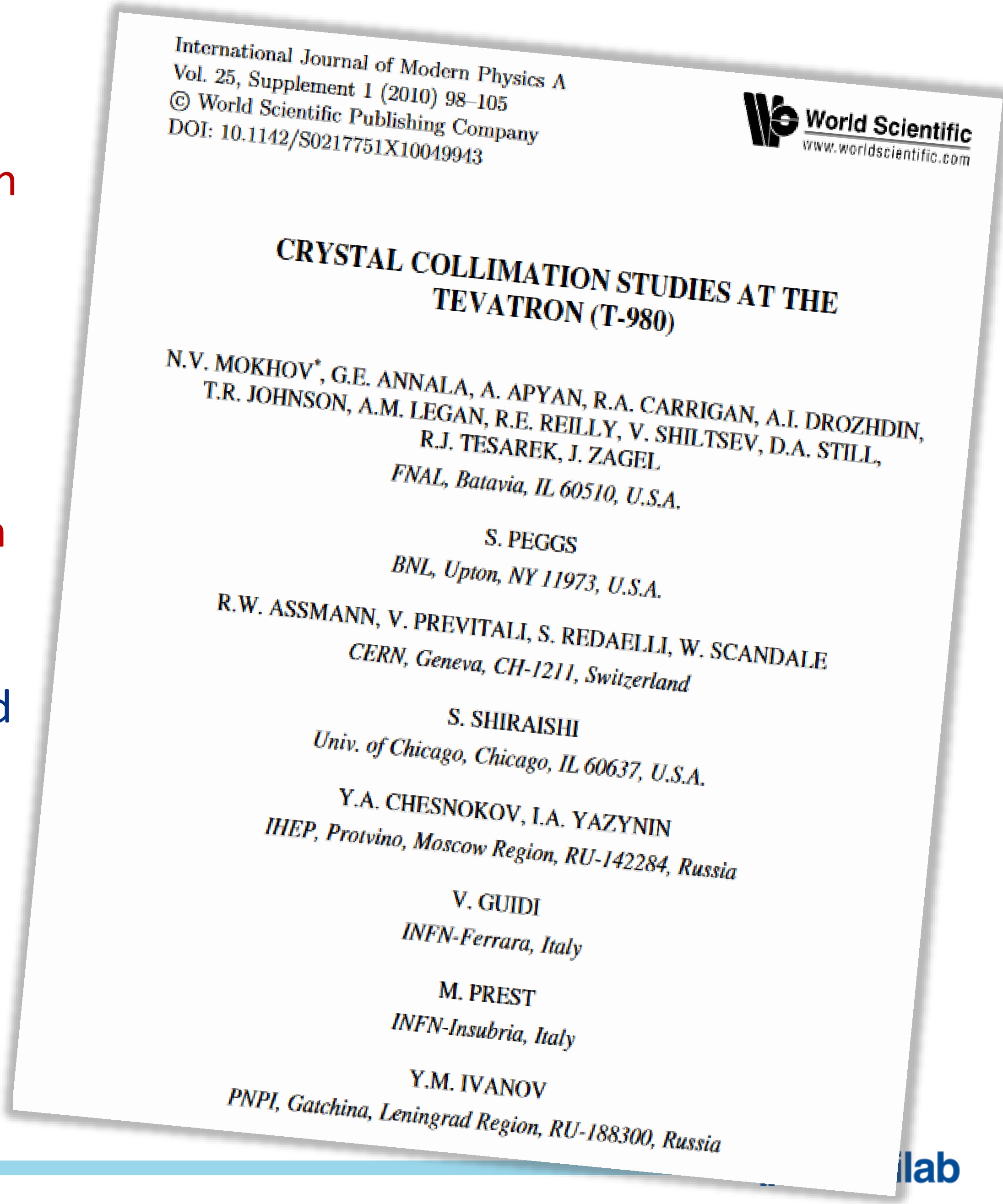






#2: 2005-2011s (T980)

First measurements at the Tevatron in 2005 have shown that using a thin silicon crystal to deflect the 1-TeV proton beam halo onto a secondary collimator improves the system performance by reducing the machine impedance, beam losses in the collider detectors and irradiation of the superconducting magnets, all in agreement with simulations.
The 2005 studies have demonstrated improved collimation efficiency with the crystal, in particular a factor of two reduction of beam losses in the CDF experiment
…followed by dedicated beam studies and first full collider stores.



International Journal of Modern Physics A
Vol. 25, Supplement 1 (2010) 98–105
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DOI: 10.1142/S0217751X10049943

CRYSTAL COLLIMATION STUDIES AT THE TEVATRON (T-980)

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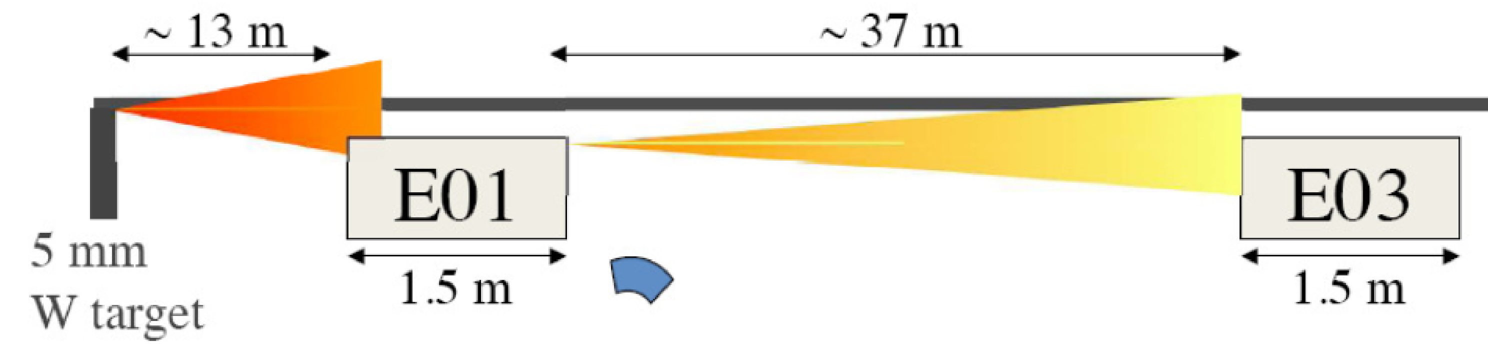
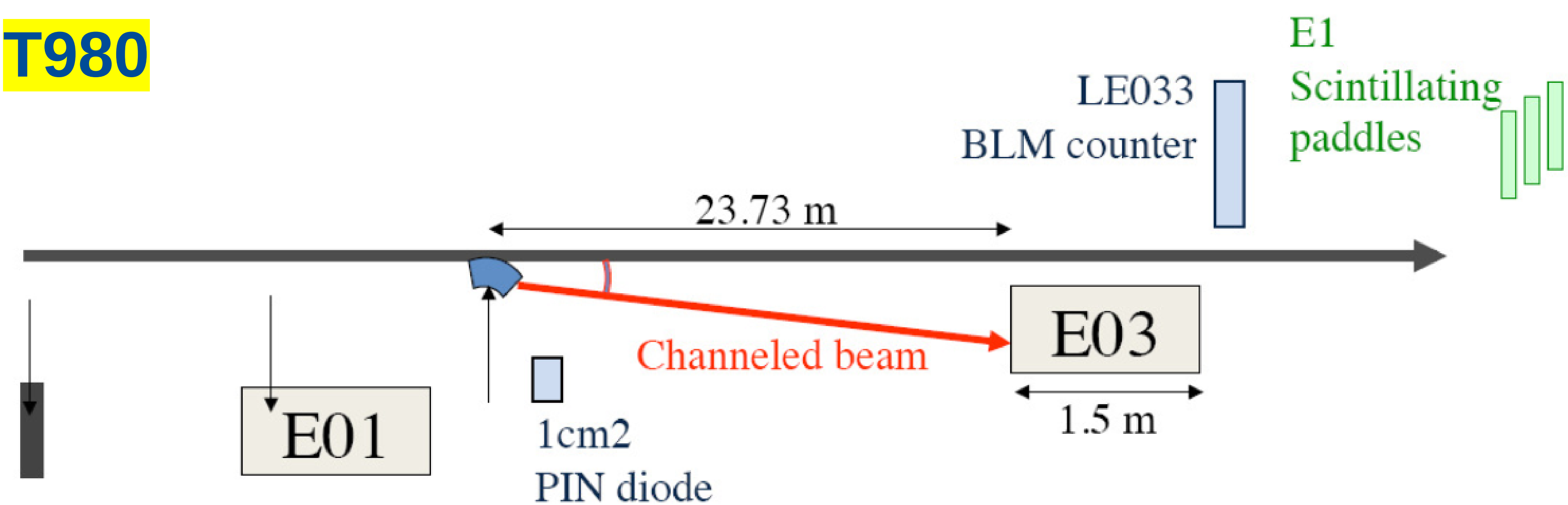
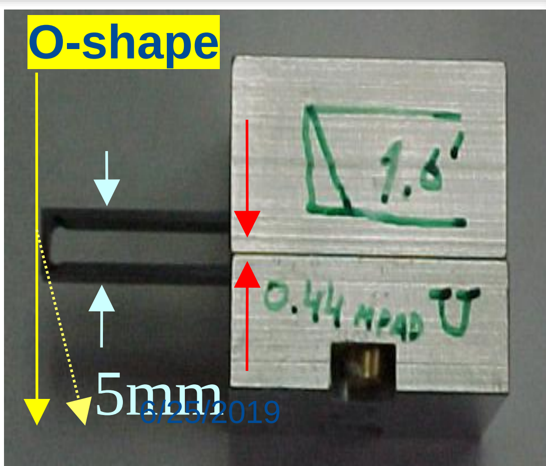
Operations



T980





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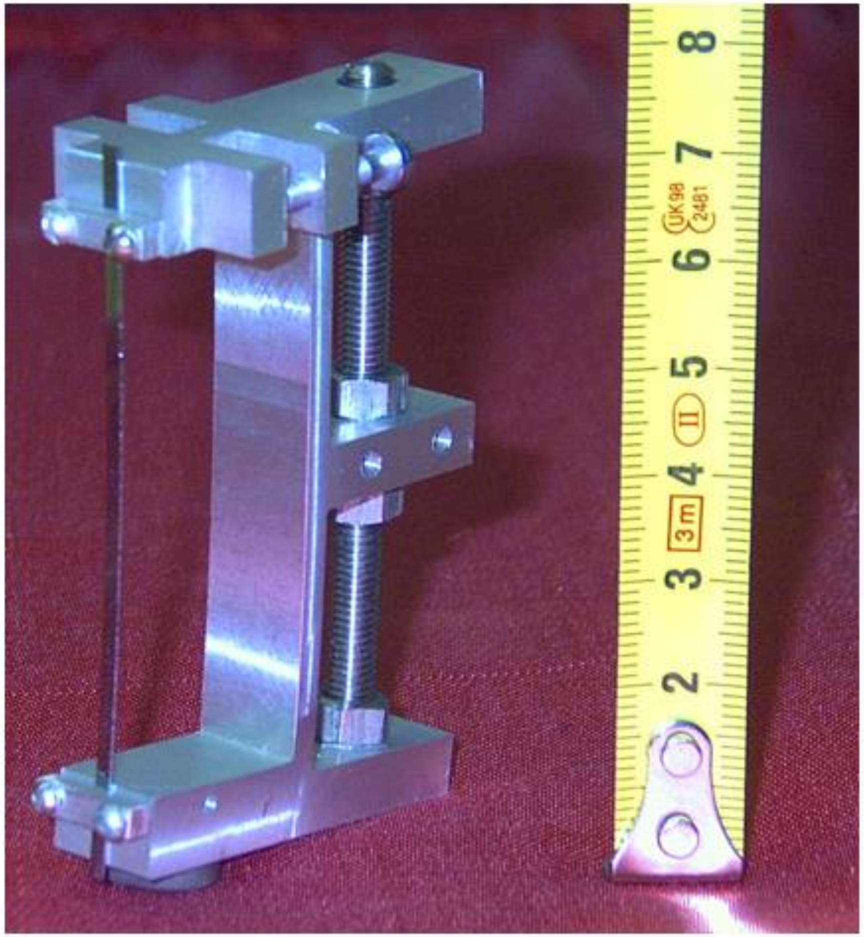
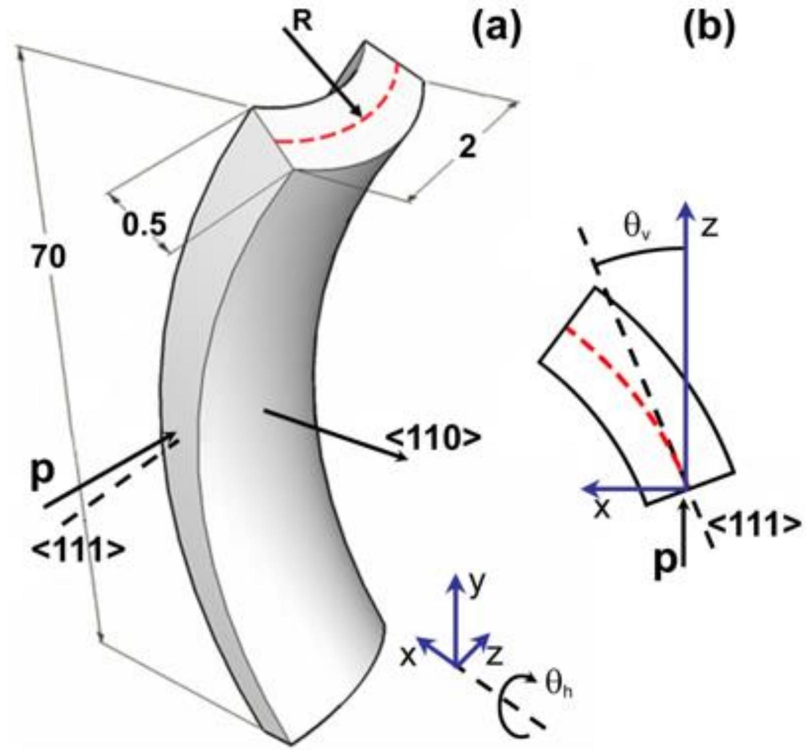
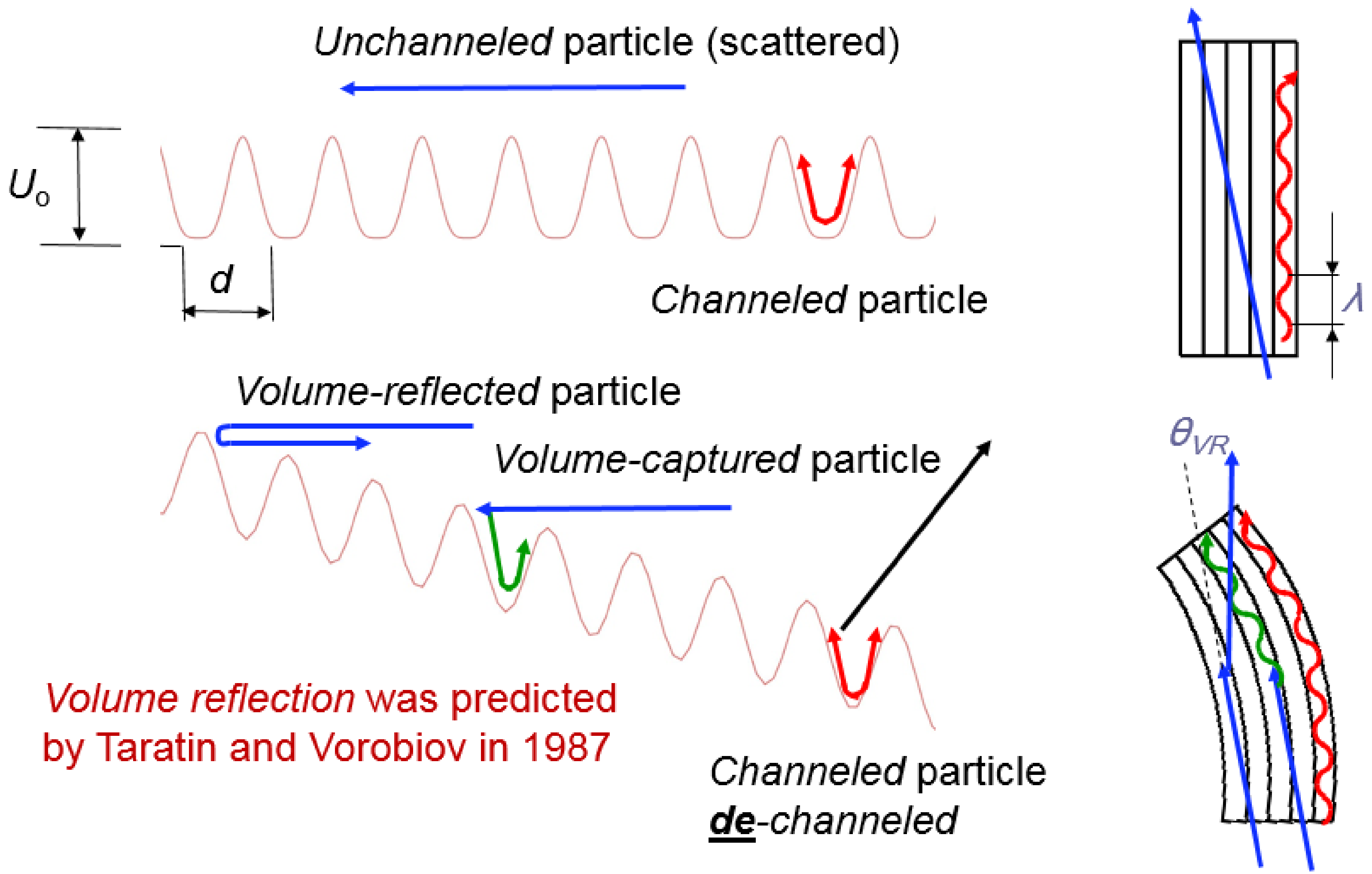
What is *bent crystal*?





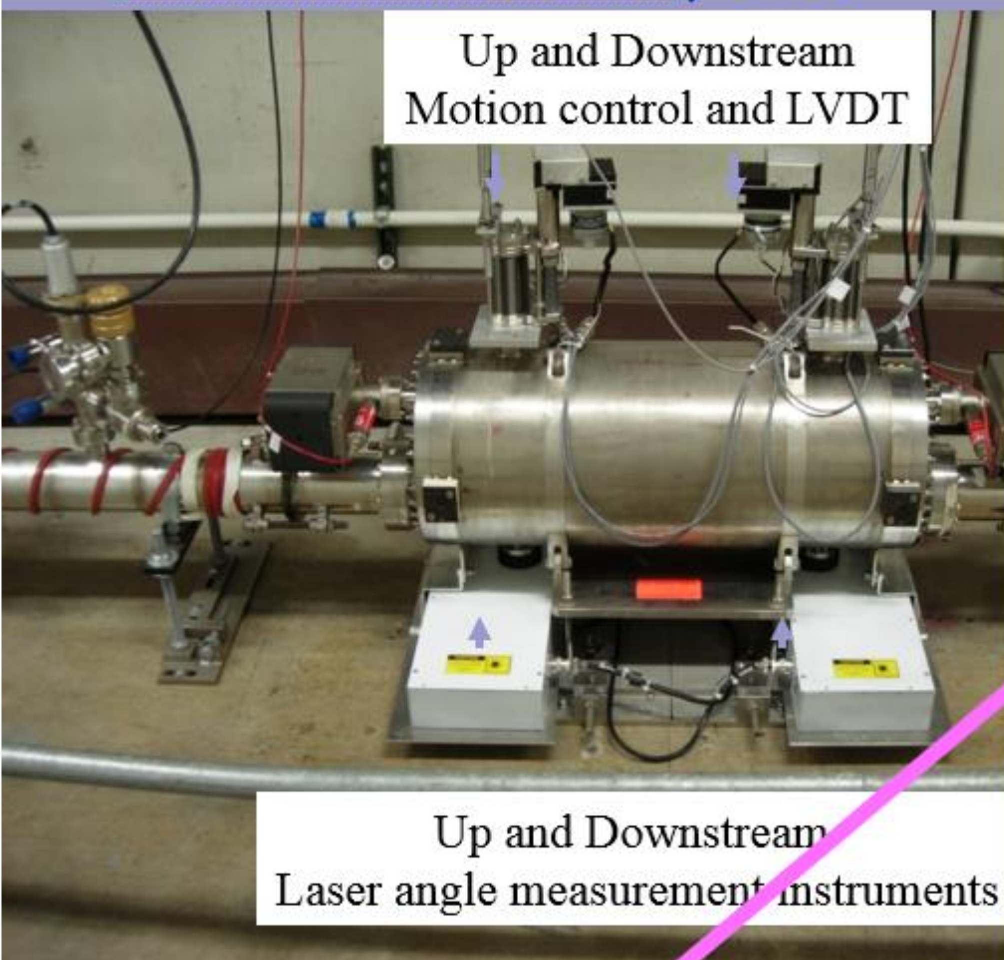
Crystal bending is accomplished through *anticlastic* deformation

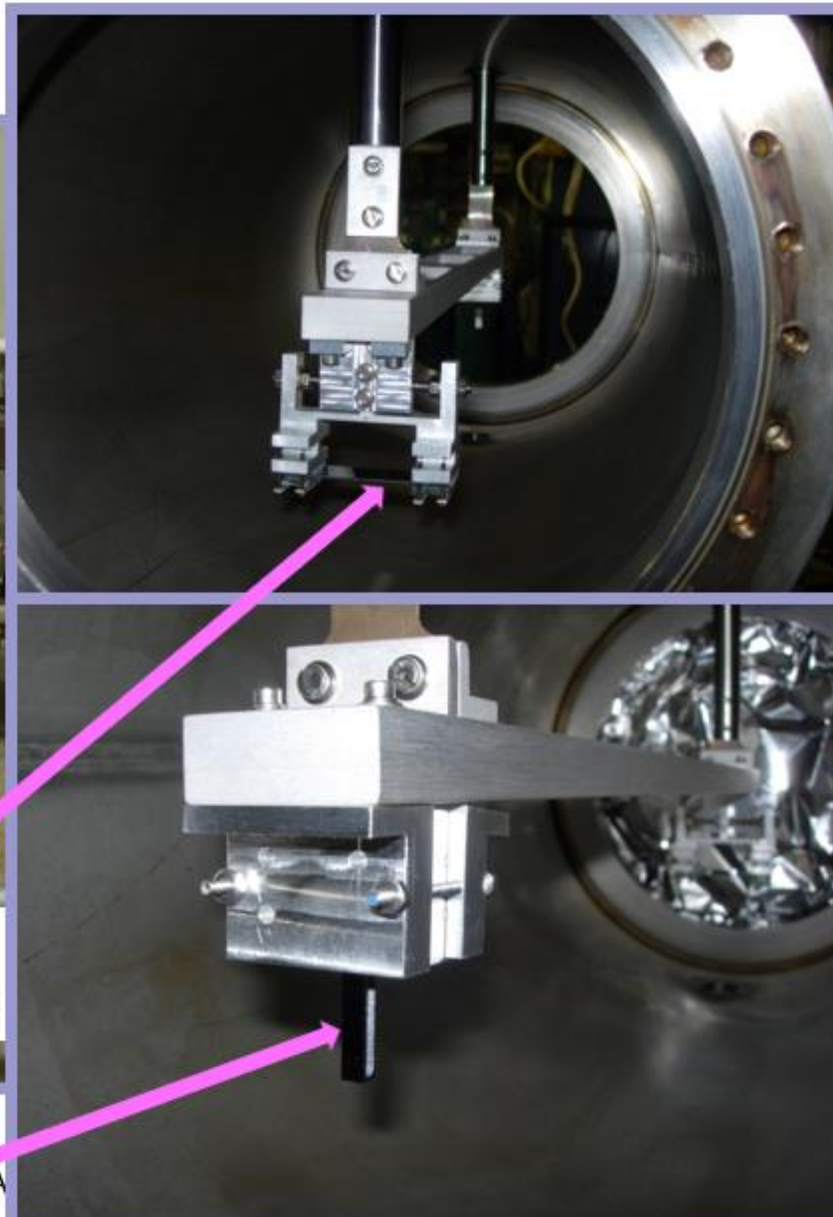
Five (!) Processes in Crystals



Volume reflection was predicted by Taratin and Vorobiov in 1987

The T980 Experiment Hardware: Goniometers, etc

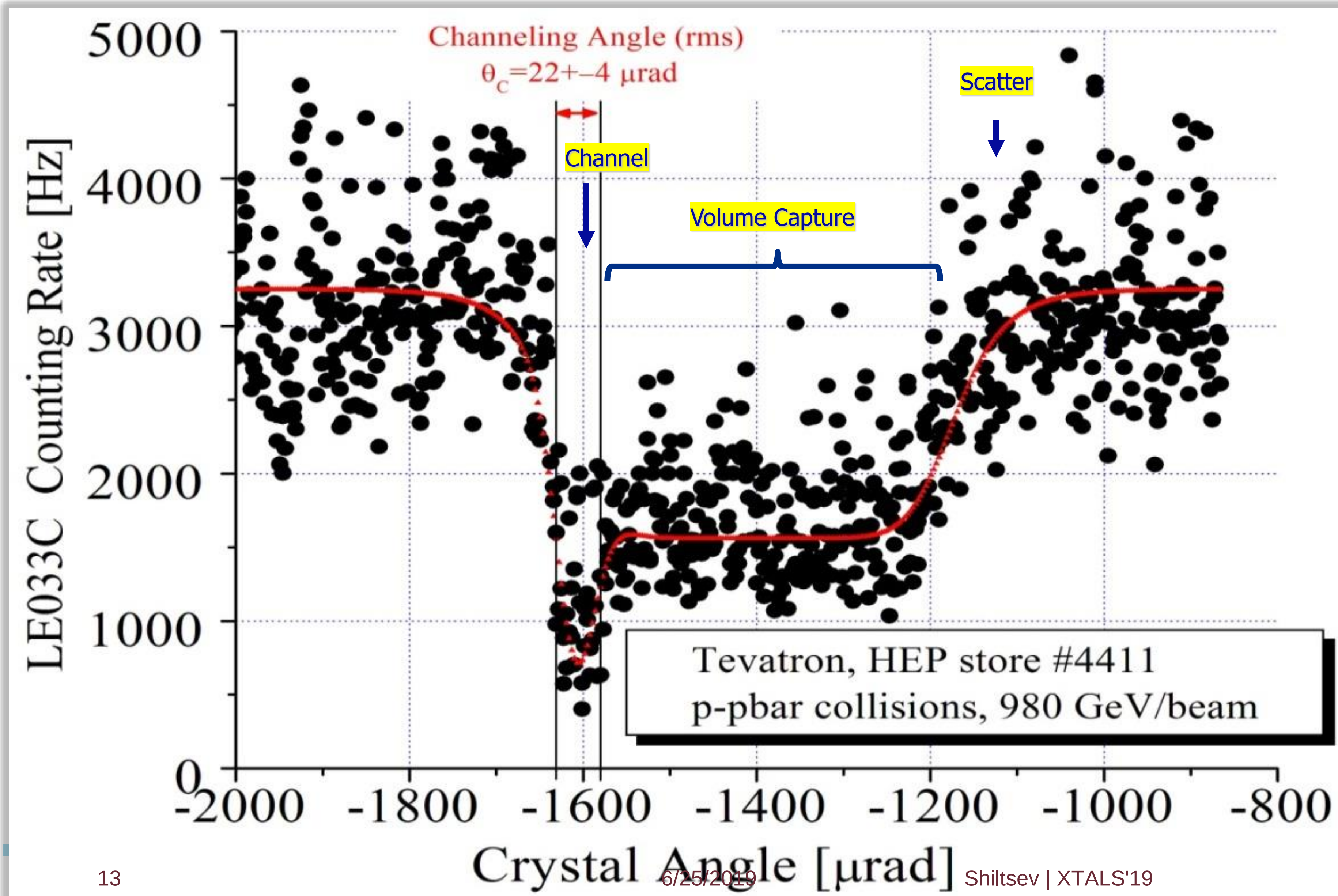




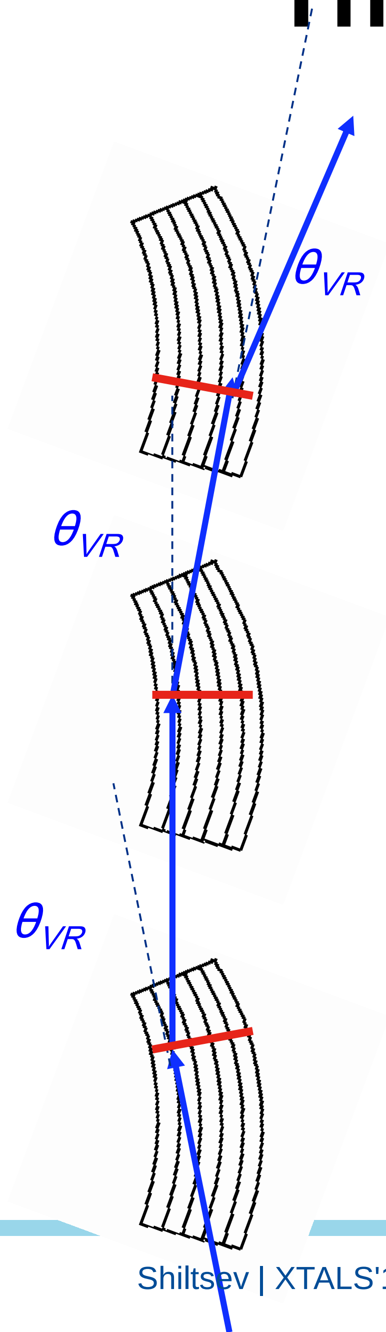
crystals

T980 : Single Crystal Results

~92.5+-5% efficiency
or *l_d* ~ 5mm/0.025 < 0.2m



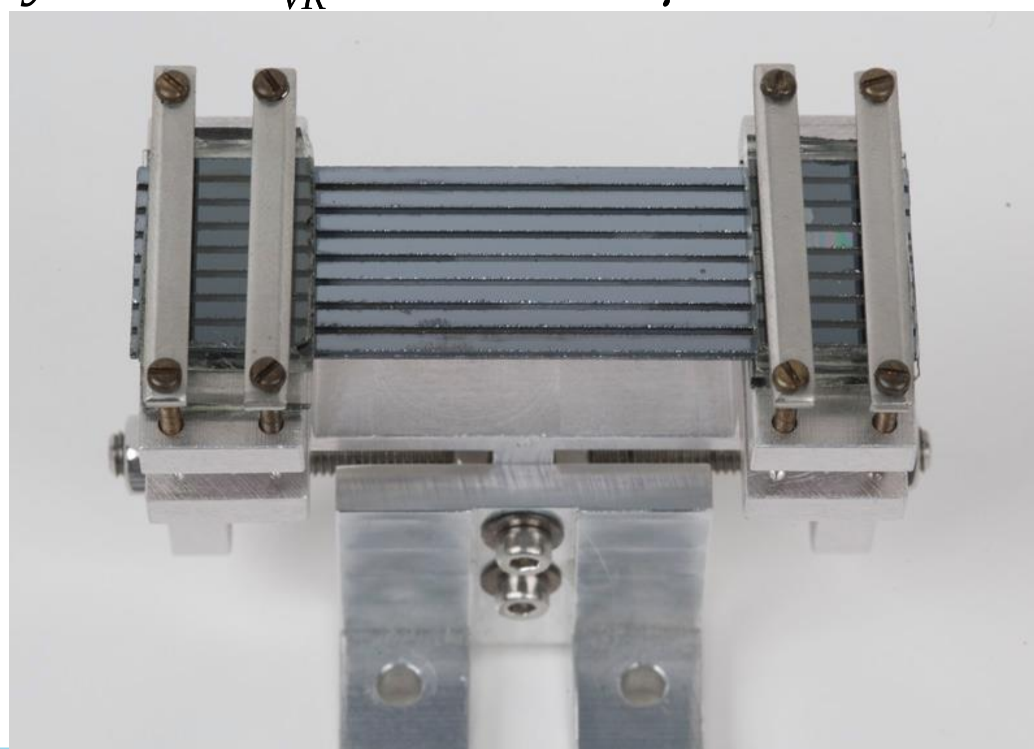
The concept of multiple VR



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

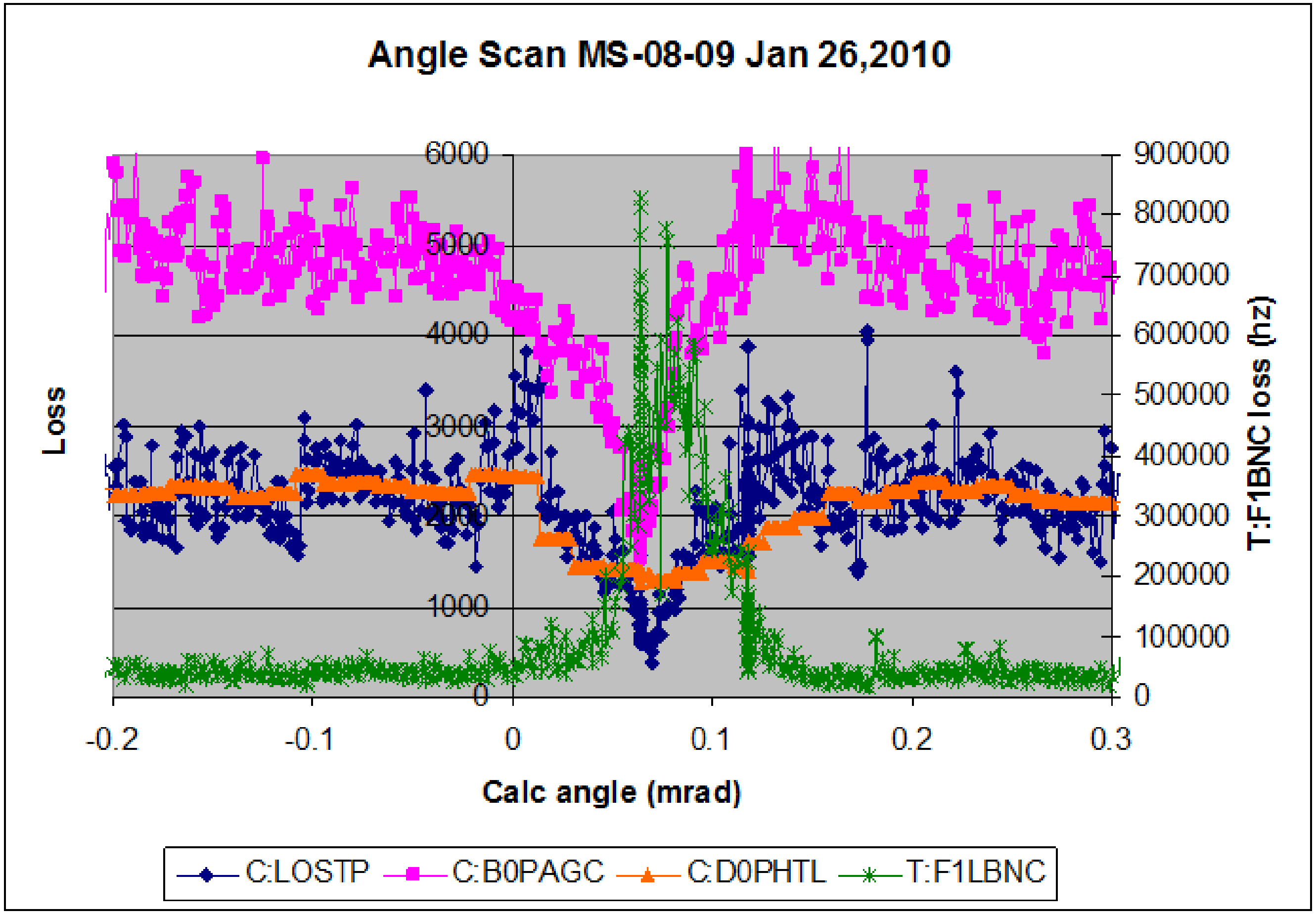
$$One\ crystal \quad \theta_{VR} = 8\mu rad; \theta_{bend} = 200\mu rad$$

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



8 Crystal “Strips” (IHEP, Protvino)

MS-08-09 angle scan w/ IP losses



Rough Measured IP loss reduction:

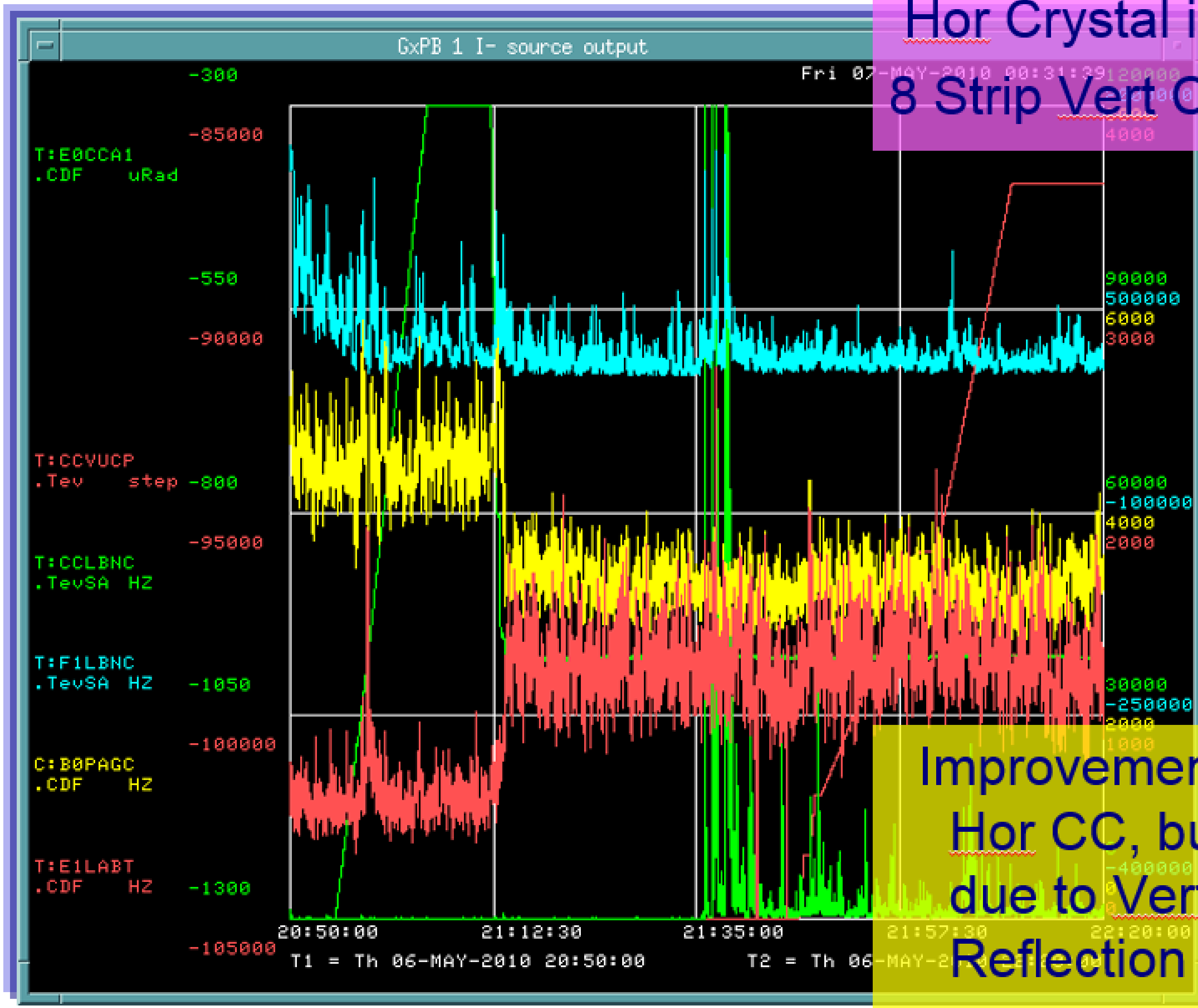
Bunch :
CDF ~ x4
D0 ~ x1.7

Abort Gap:
CDF ~ x3

T-980

1st Attempt of 2 Plane Crystal Collimation

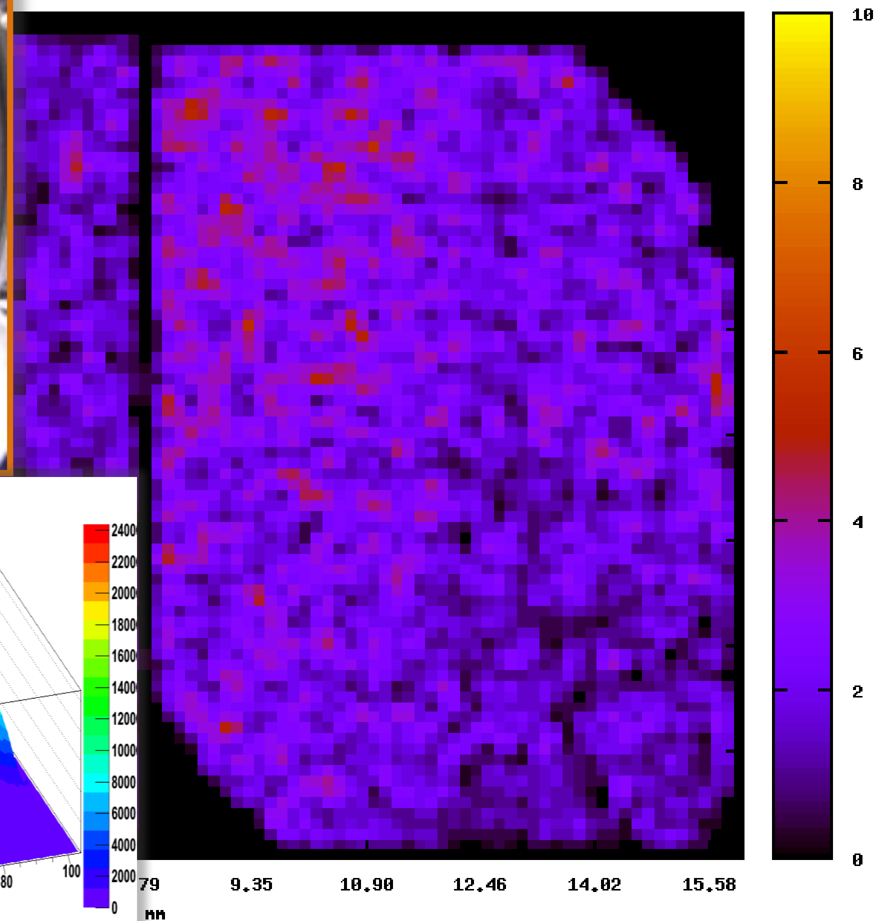
Hor Crystal in Channeling & 8 Strip Vert Crystal in VR

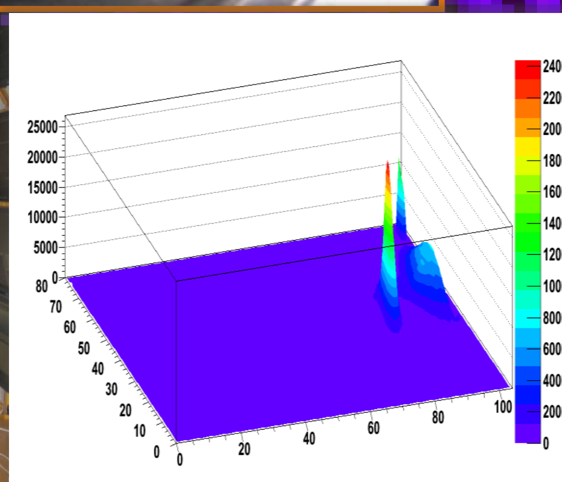


Improvement seen due to Hor CC, but very little due to Vert MS Volume Reflection

Pixel Telescope Detector

T980:Pixel Detector Image of Channeled 980 GeV Beam





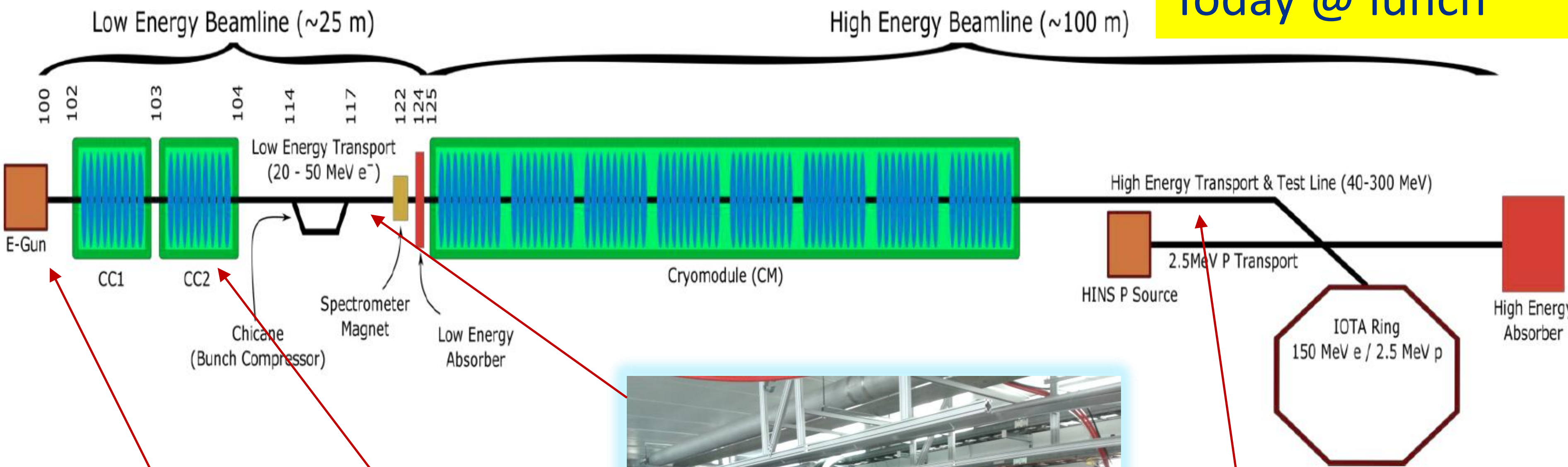
Summary Crystal Collimation in Tevatron

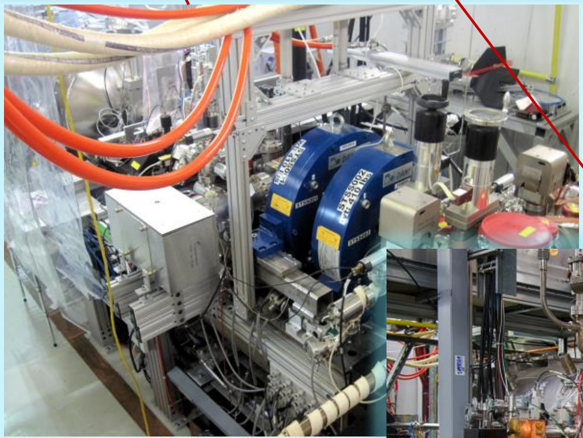
- ☑ Crystal collimation has been used during many collider stores in 2009-10
- ☑ In 2009, old O-shaped crystal in horizontal goniometer was replaced with new 0.36-mrad O-shaped one (IHEP) with negative 0.12-mrad miscut angle; PLUS, new vertical push-pull goniometer installed 4-m upstream, housing two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

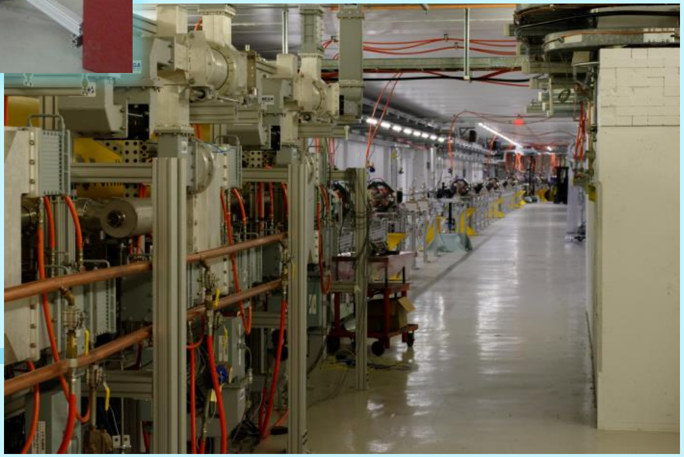
T-980

#3: Crystal experiments at FAST

Tour of FAST/IOTA
Today @ lunch





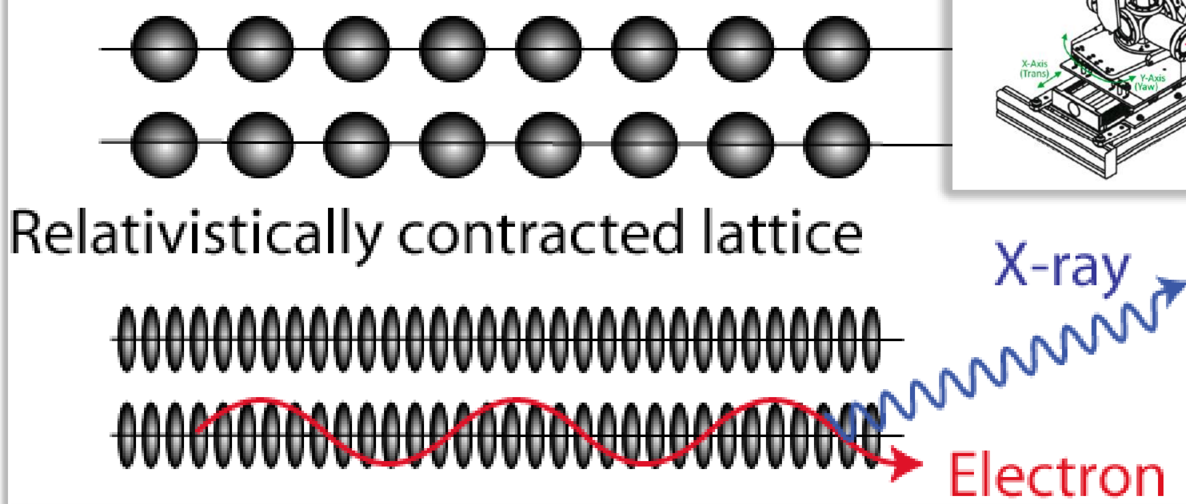


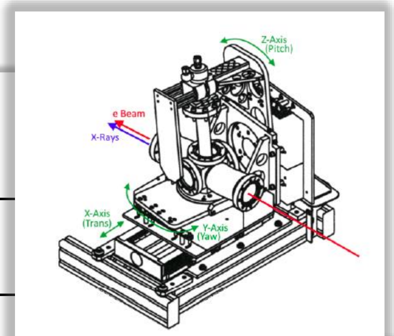
FAST Electron Beams vs Specs

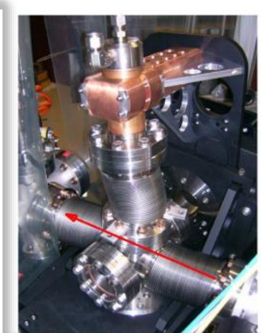
Parameter	FAST 2019	(ILC) specs	Comments
Max beam energy low-energy area electron gun	301 MeV 20-50 MeV 4-5 MeV	300 MeV	100 MeV for IOTA Typical 34-43 MeV Typical 5.5 MeV
Bunch intensity	0.1-3.2 nC	3.2 nC	Typical 0.5nC , depends on # bunches
# bunches per pulse	1-1000	3000	Typical 100, rep rate 3 MHz (max 9)
Pulse length (beam)	upto 1 ms	1.0 ms	Typical 0.01-0.2 ms
Pulse rep rate	1 Hz	5 Hz	See above
Tr. emittance (n, rms)	1-5 μm	5 μm	Grows with bunch intensity
Bunch length, rms	1.2-2.4 mm	~1 mm	w/o compression

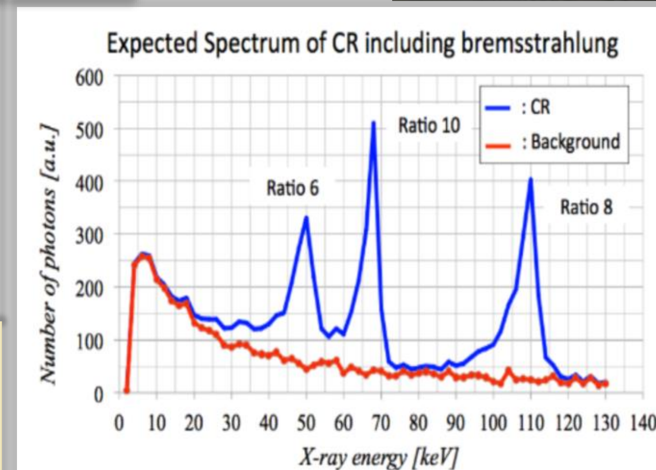
2015-2017 CRYSTAL CHANNELING EXPT @ FAST

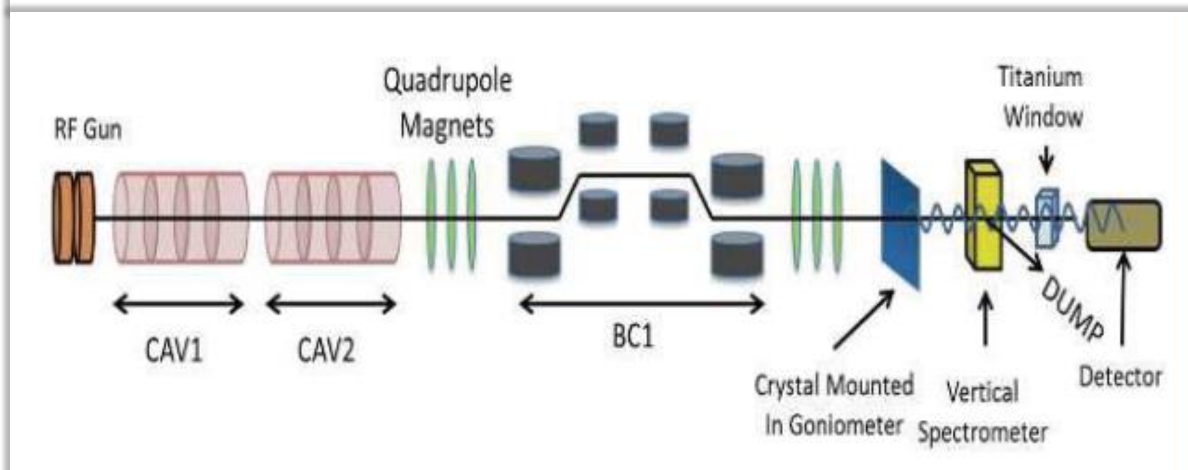
- P.Piot, T.Sen, A.Halavanau, D.Edstrom, J.Hyun, et al
- helpful experience

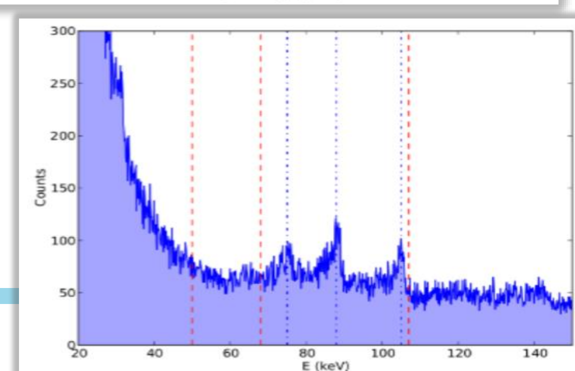




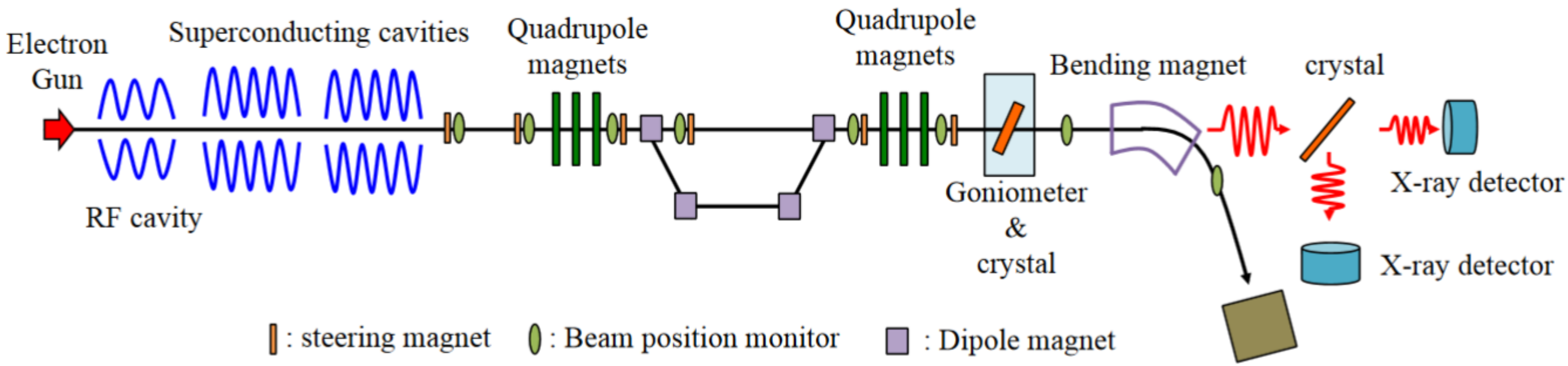








arXiv:1612.07358

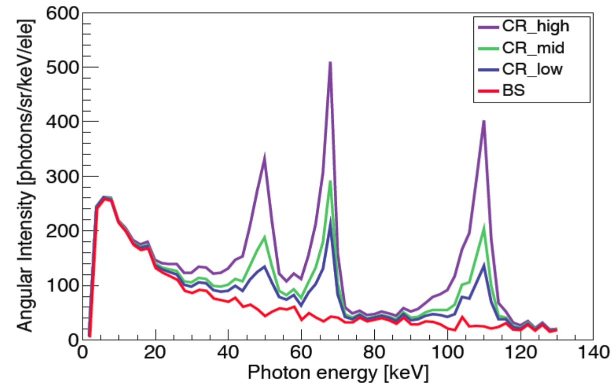


Xtal radiation exp’t at FAST

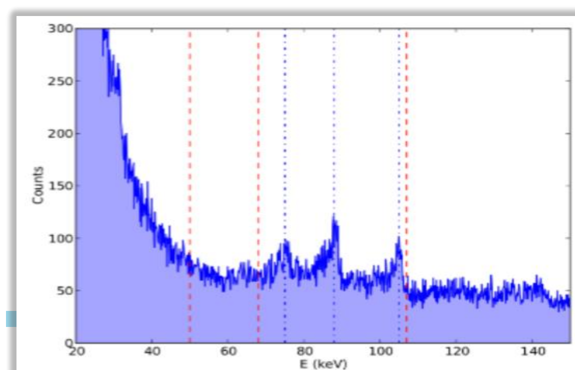
- diamond single crystal with a thickness of 168 μm
- For *E*=43 MeV and the (110) plane, critical angle is 1.1 mrad
- Careful analysis of errors and backgrounds

arXiv:1802.06113

- J. Hyun
- P. Piot
- T. Sen



Beam energy	43 -50 MeV
Bunch charge	1-200 pC
Bunch frequency	3 MHz
Normalized emittance	0.52 mm-rad
Bunch length	3 pC
Energy spread	< 0.2%

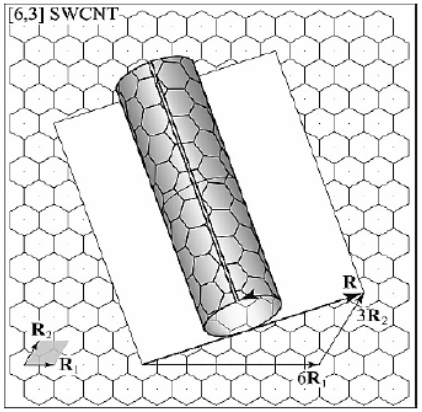


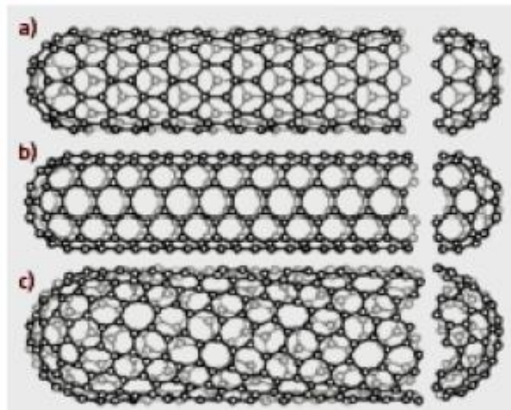
Y.M.Shin *et al* CNT proposal (2012-2015)

Nuclear Instruments and Methods in Physics Research B 355 (2015) 94–100

- Carbon Nano Tubes (CNTs)

Rolling single graphene-sheet



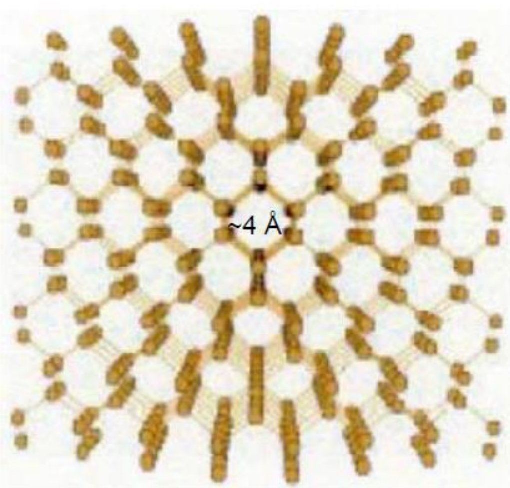


Ends usually closed

→ Possible advantages over crystals

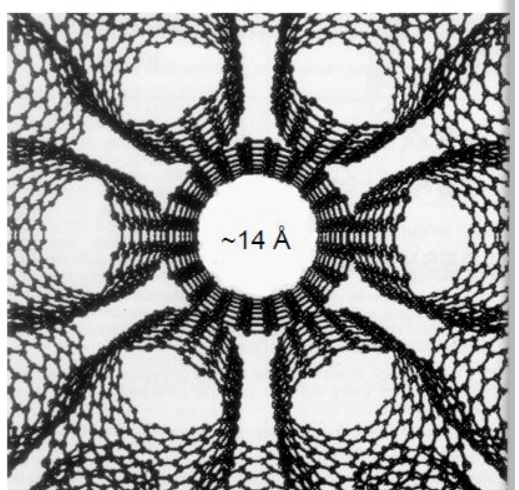
- **Wider channels: weaker de-channeling**
- **Broader beams (using nanotube ropes)**
- **Wider acceptance angles (< 0.1 rad)**
- **Lower minimum ion energies (< 100 eV)**
- **3-D control of beam bending over greater lengths**

Front view of (110) channels in Si crystal

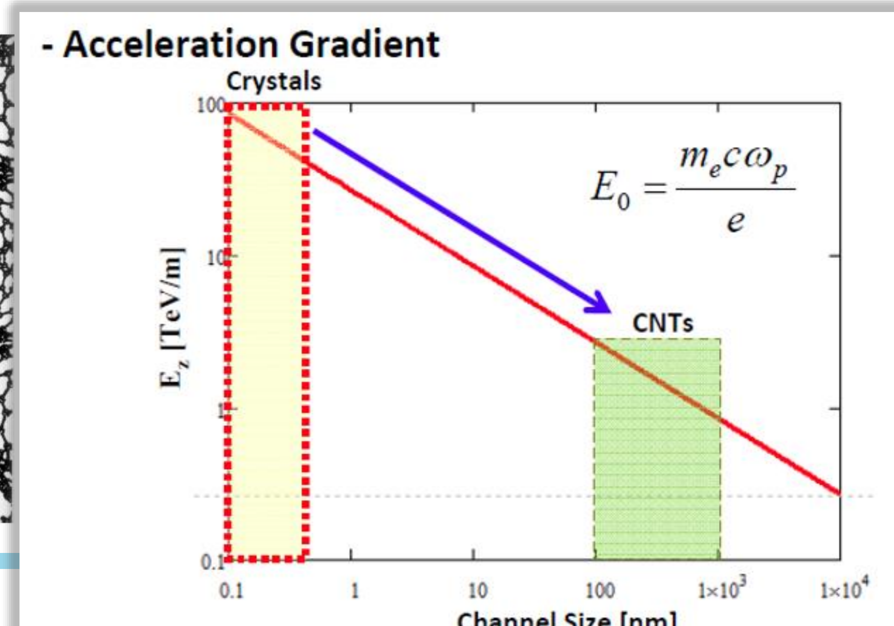


Lattice Constant of Unit Cell ~ 4 A

Entrance to a rope of (10,10) SWNTs

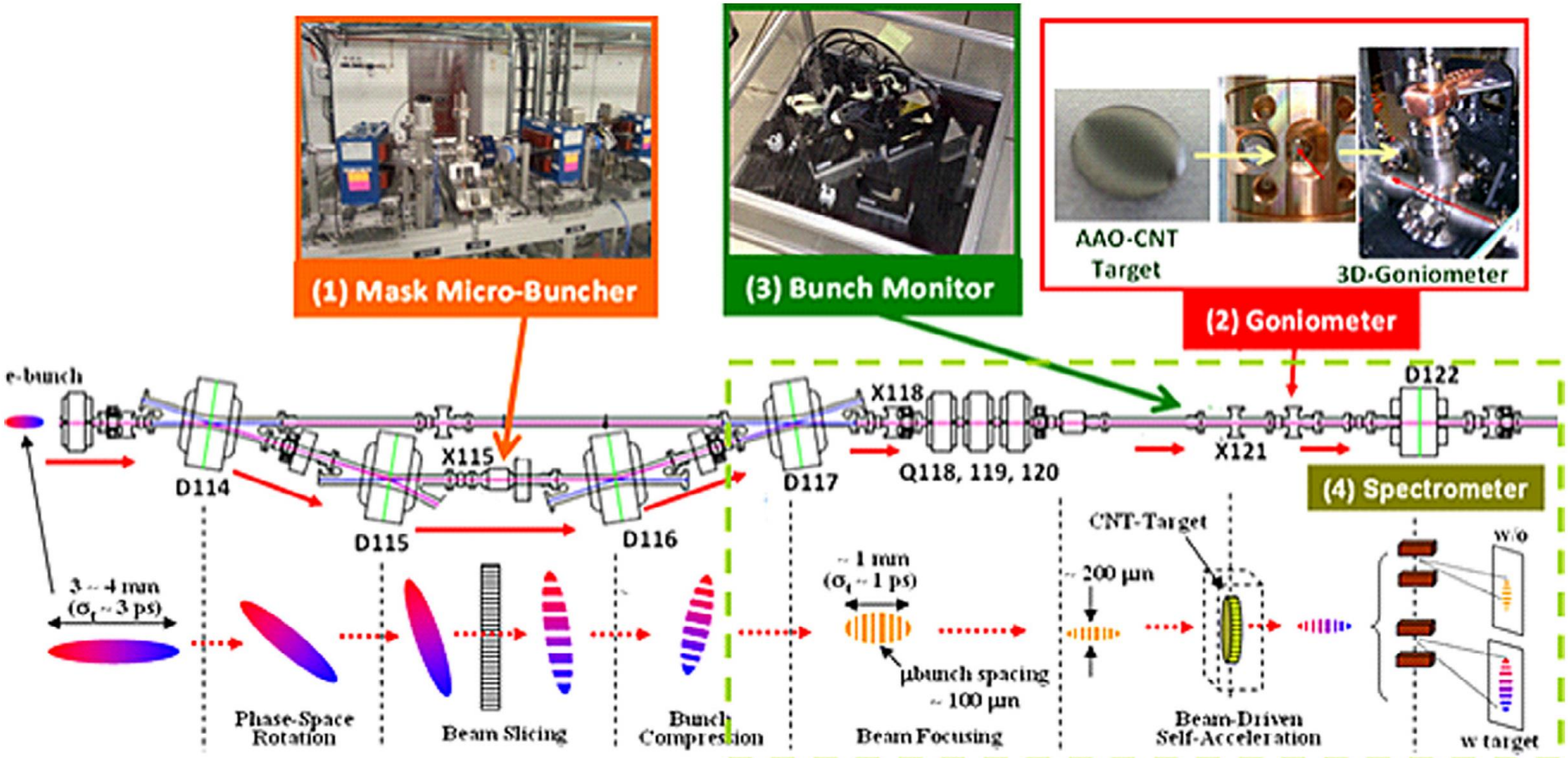


Lattice Constant of Unit Cell ~ 14 A



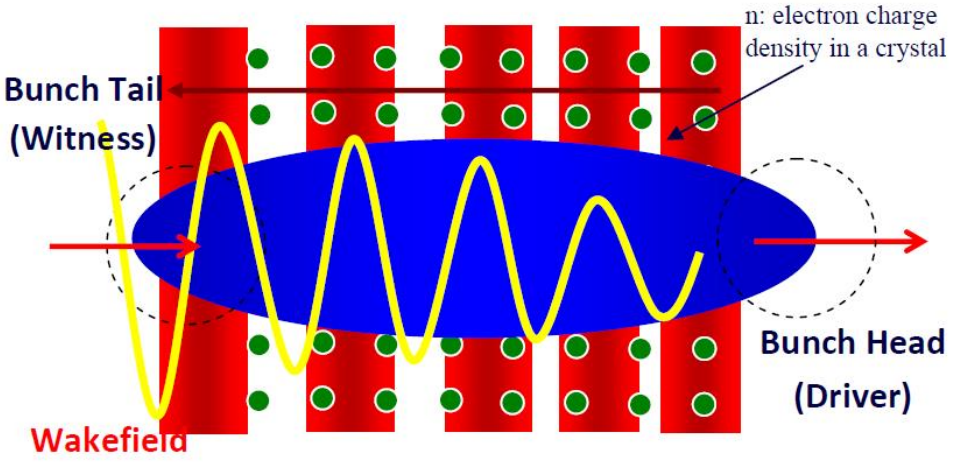
Y.M.Shin et al: CNT Experiment at FAST

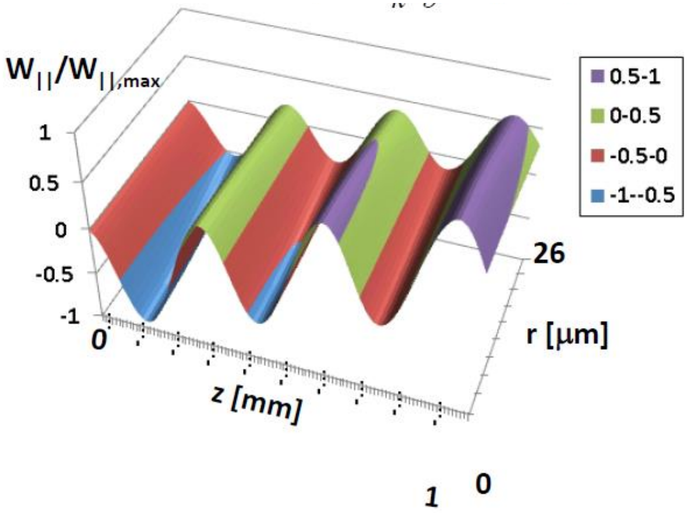
Slit-mask micro-bunching
1 nC; $\lambda_{mb} = 100\ \mu m$



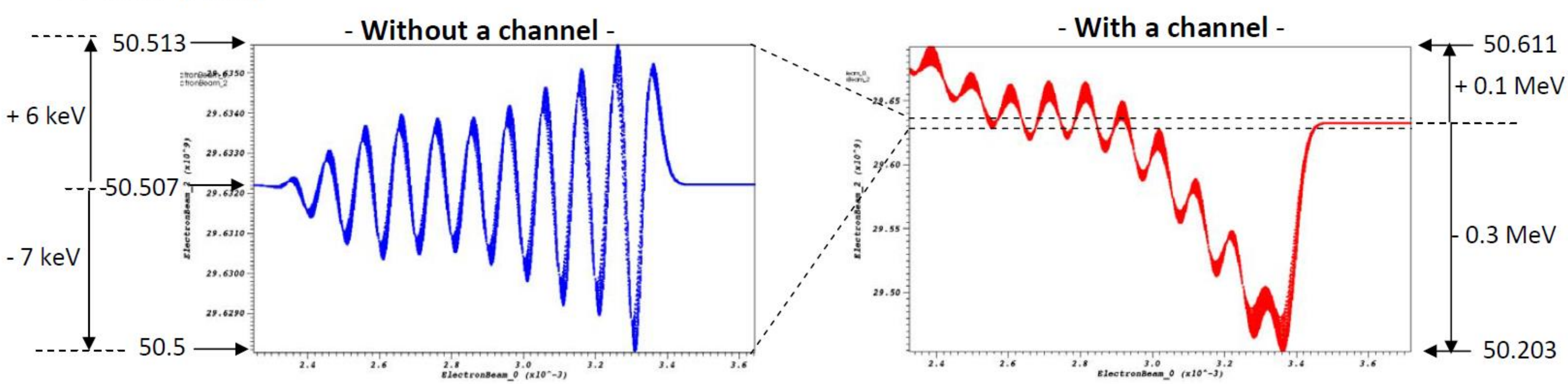
Wakes in the Carbon Nano Tubes

Y.M.Shin(NIU/FNAL),
C.Thangaraj (FNAL), et al



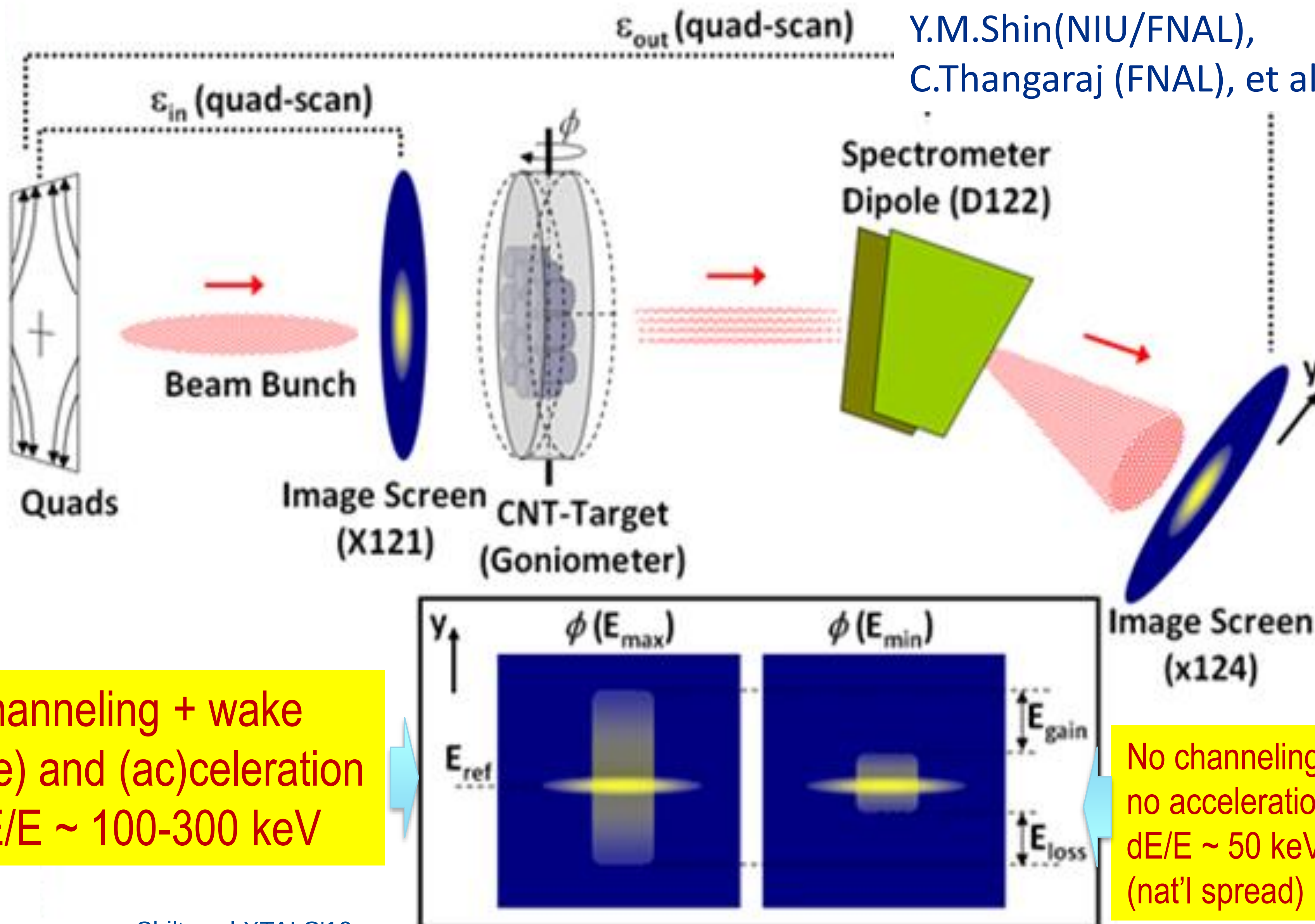


- 50 MeV (1 nC)



CNT Experiment at FAST (proposal)

Y.M.Shin(NIU/FNAL),
C.Thangaraj (FNAL), et al



Channeling + wake (de) and (ac)celeration dE/E ~ 100-300 keV

No channeling/ no acceleration dE/E ~ 50 keV (nat'l spread)

YM.Shin Collaborators on Simulation on Crystal Acceleration

- Bormann Anomalous Transmission

→ HFSS (M.-C. Lin: Tech-X)

→ CST MWS (A. Gee, Y.-M. Shin: NIU)

→ VORPAL (M.-C. Lin: Tech-X)

- Channeling X-ray Acceleration

→ VORPAL (M.-C. Lin: Tech-X)

→ CST PIC (A. Gee, Y.-M. Shin: NIU)

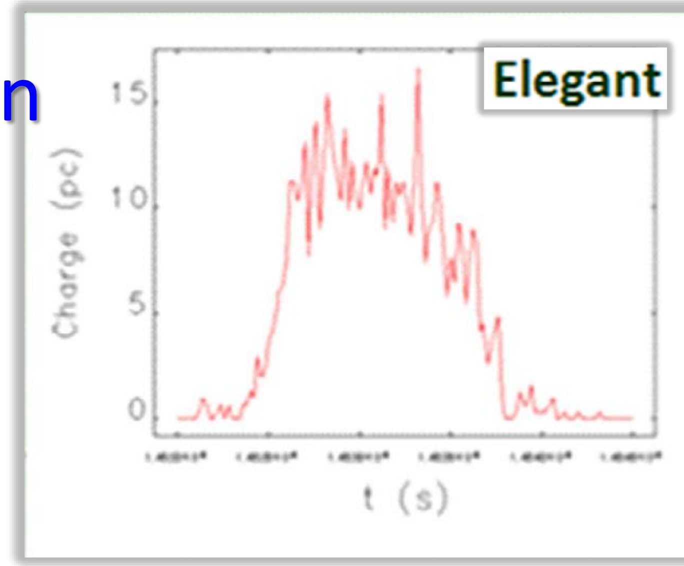
→ CHEXAST (Channeling effect and X-ray accelerator sim

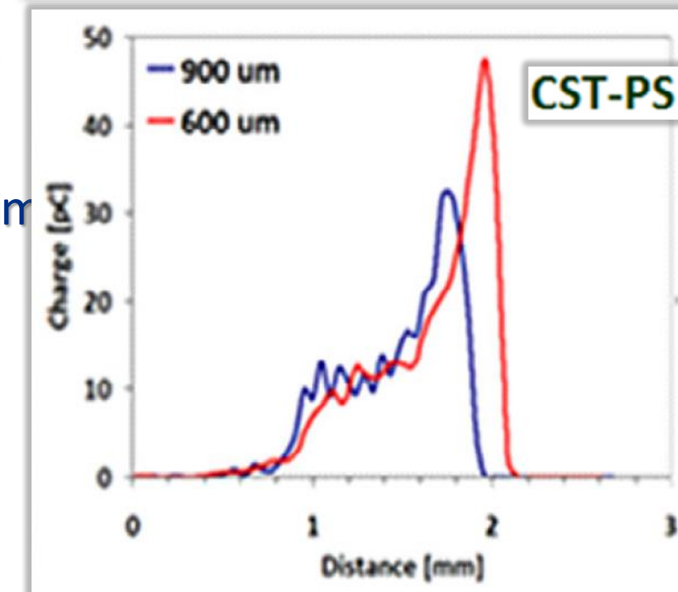
(Alexei Sytov, V. TIkhomirov: Belarusian State Univ.)

- Crystal Plasma Wakefield Acceleration

→ VORPAL (M. –C. Lin: Tech-X)

→ CST PIC (A. Gee, Y.-M. Shin: NIU)





Slit-mask micro-bunching simulations

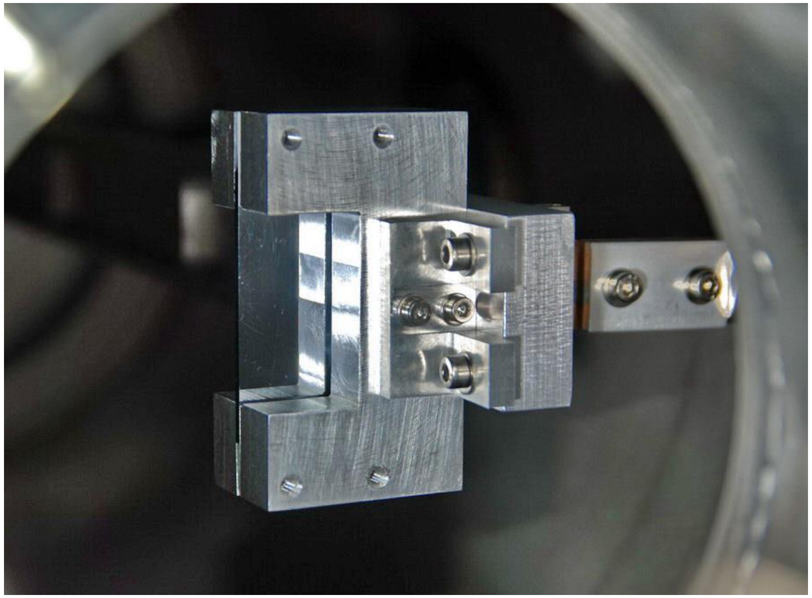
Summary

- Fermilab has some 25 year long history of research and operation of crystals in high energy proton accelerators:
  - pioneering experiment E853 on crystal assisted extraction by R.Carrigan, et al during the Tevatron Collider Run I
  - T980 crystal collimation experiment in 2005-2011 by N.Mokhov et al (paved the way to similar one in the LHC)
- FAST linac at NML offers opportunities for channeling of electrons :
  - Xtal radiation experiment
  - CNT channeling proposal
- Significant experience and availble hardware can be very helpful for future exploration toward acceleration in crystals and nanostructures: i) pre-FACET-II experiment detectors and integration; ii) CNT channeling; iii) muon production/capture

Thank You for Your Attention!

Similar QM crystals used for UA9 measurements at SPS in 2009.

Feature: short bending length,
smaller nuclear interactions



Opening in bending device 2x10 mm^2

2-mm thick, 120-μrad bending, miscut angle 50 μrad

Characterized, tested and installed in the vertical IHEP goniometer.

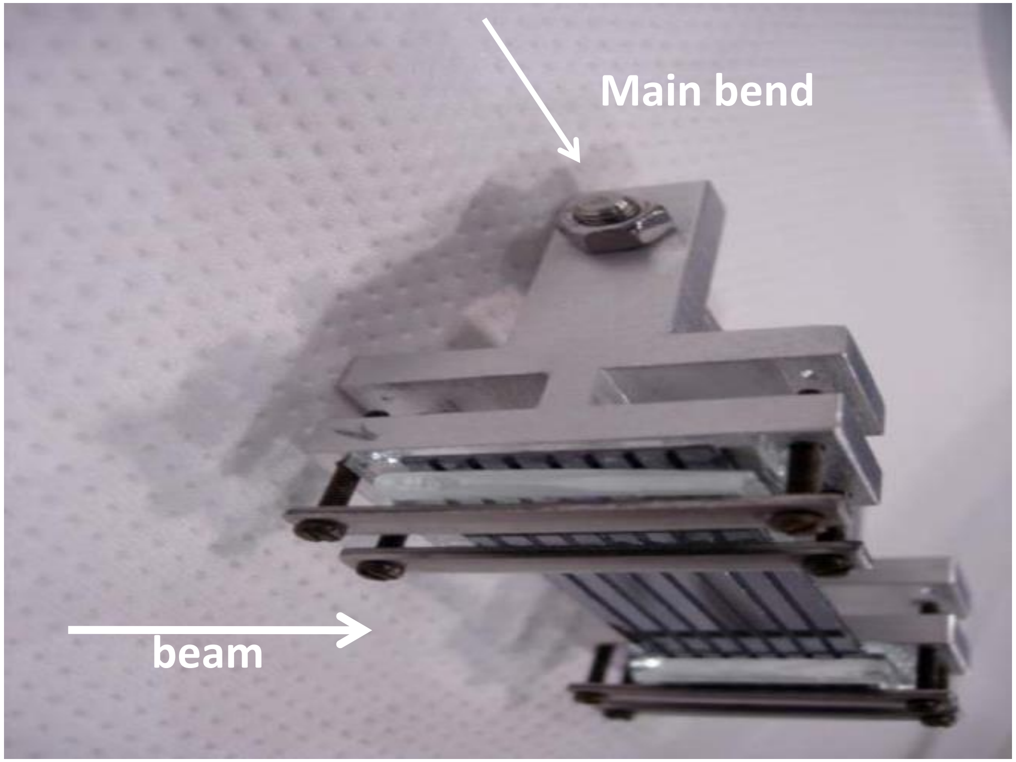
Problem – no clean evidence of CH or VR in five dedicated End-of-Store (EOS) sessions over last three months!

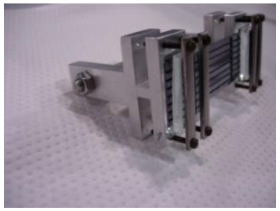
Ivanov asks if in later turn it hits aluminum holder?

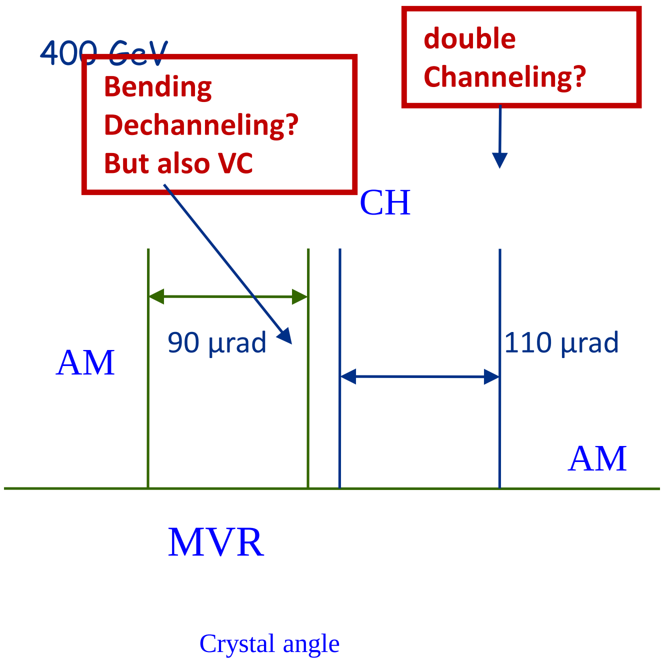
Pin counter nearer horizontal? Maybe a 2nd pin?

BLMs out of time? Now being checked

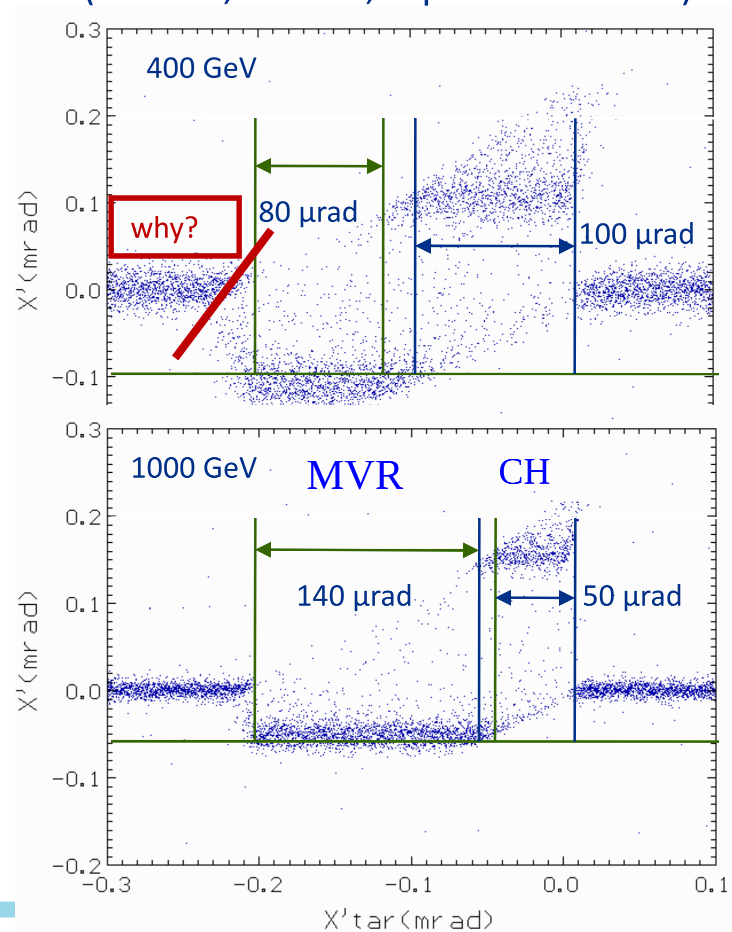
- interesting example of volume reflection
- well studied earlier at H8 and in simulations
- may also indicate a few challenges

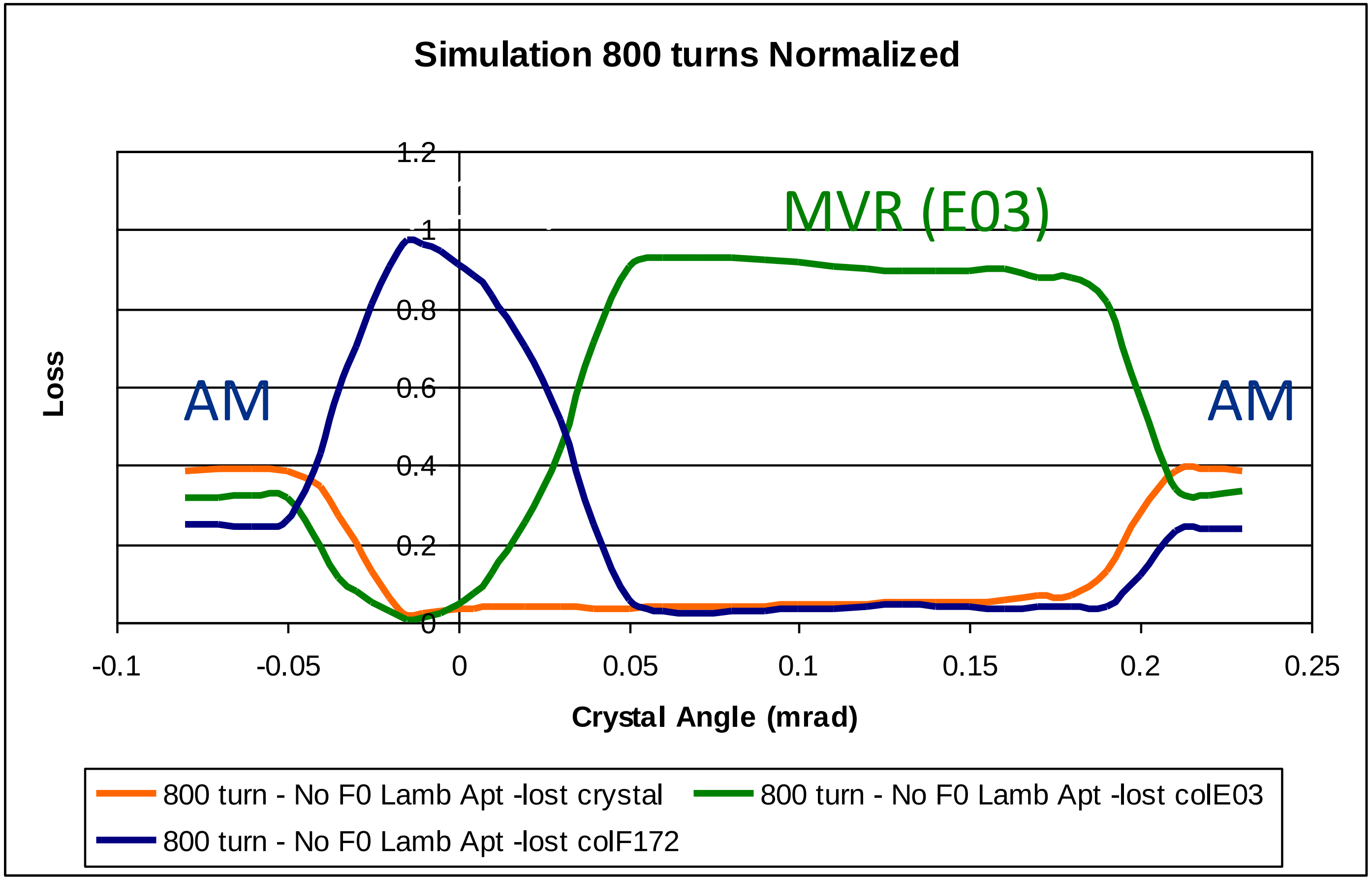






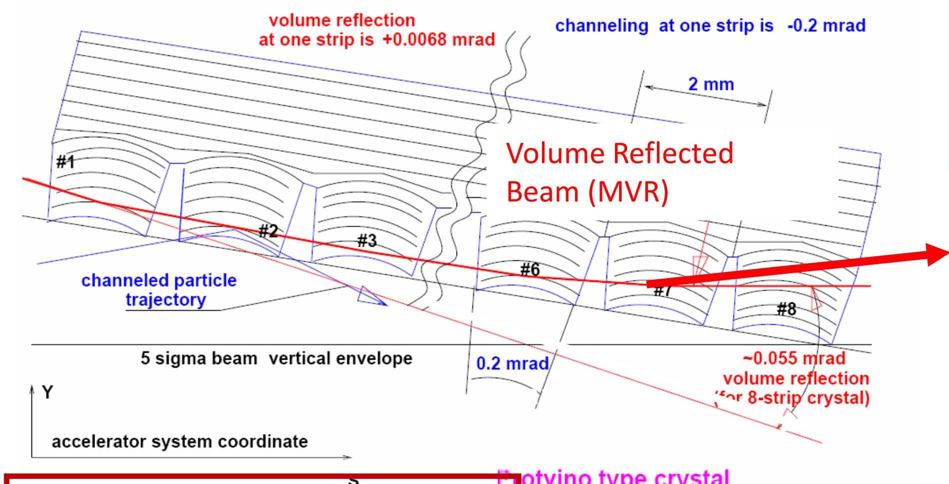
Yazynin simulation
8 Ideal strip crystals Si(111) "array"
(L=2mm, R=10m, Alpha = 200 urad)





Simulations by:

S. Drozhdin with imbedded code from I. Yazynin

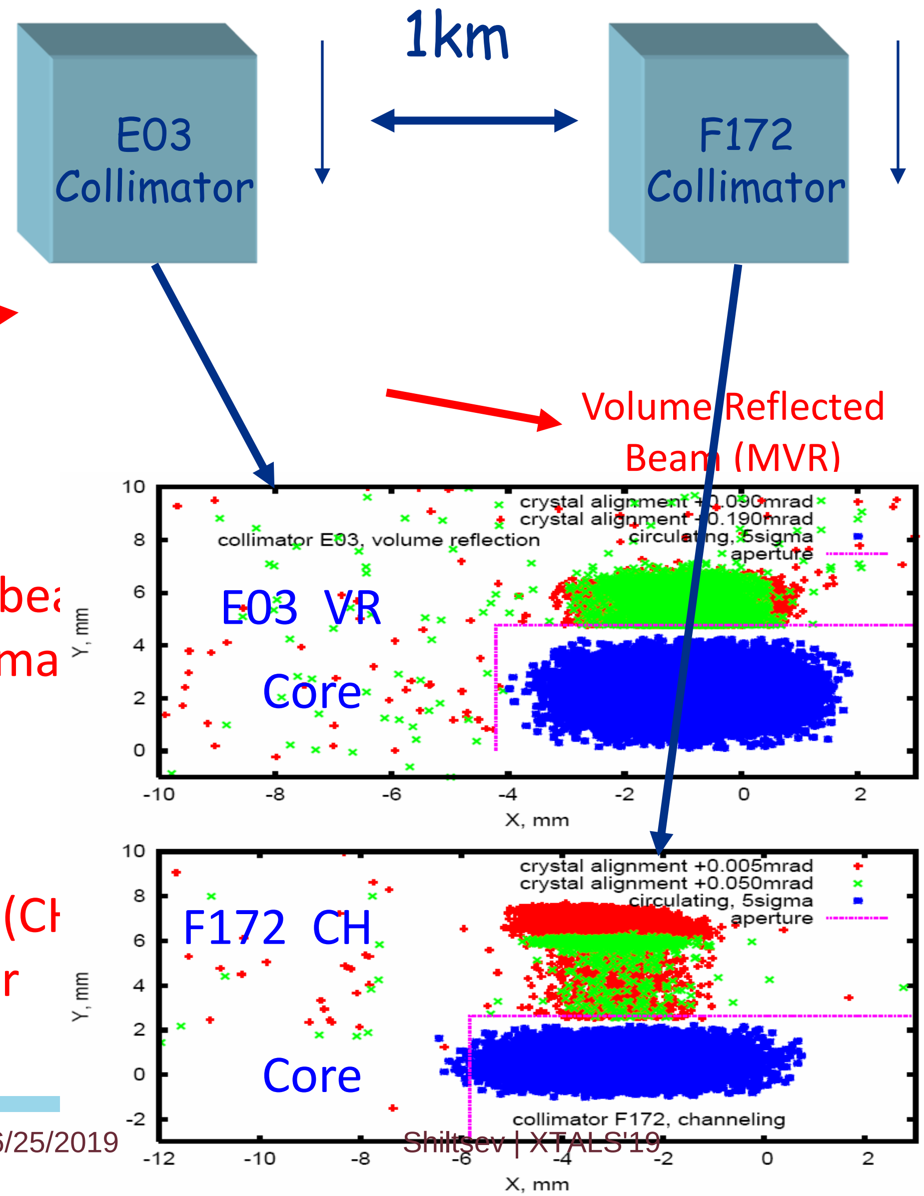


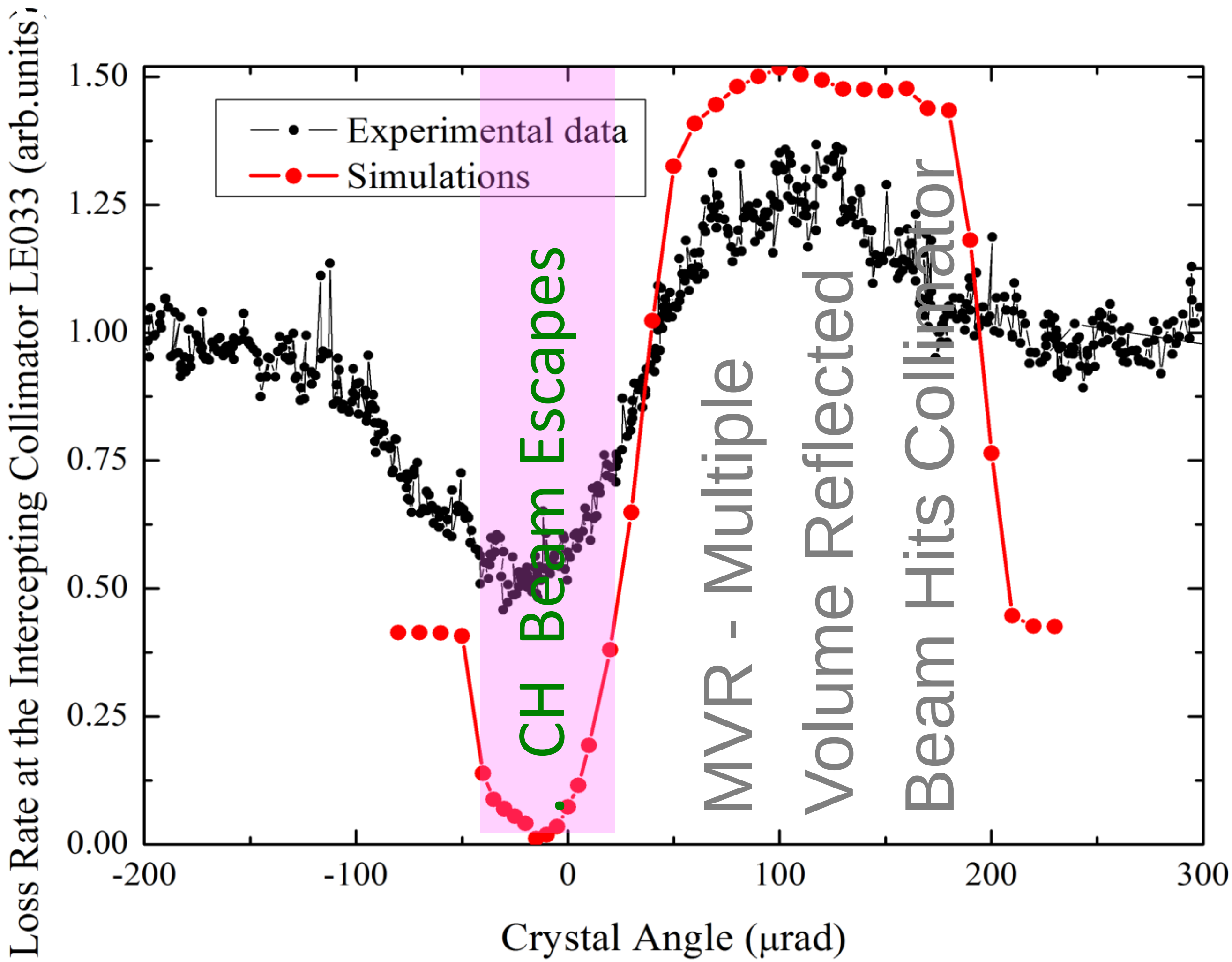
Watch out!
Si wafer may not be flat

Volume Reflected bea
(MVR) at E03 Collima

Drozhdin simulation

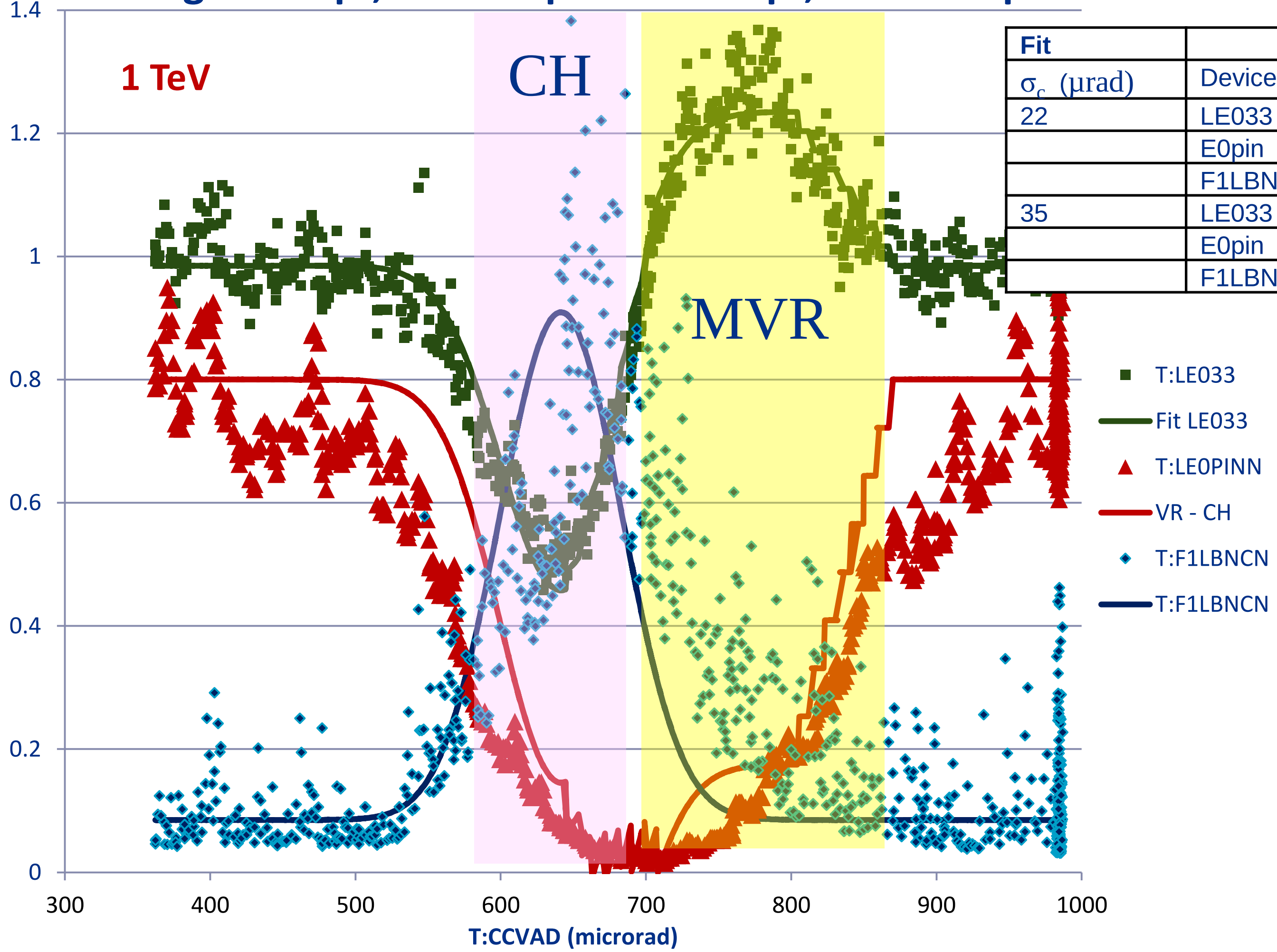
Channeled Beam (CH
at F172 Collimator





Simulations by:
S. Drozhdin with imbedded code from
I. Yazynin

Angle scan IHEP 8 strip - vert. coll. fit to E033
sig c = 35 μr, interstrip offset = 9 μr, VR = 160 μr



Fit			2/4/2011	
σ_c (μrad)	Device	A_{CH}	A_{VR}	Chi sq
22	LE033	0.86	0.21	0.084
	E0pin	0.875	0.665	0.154
	F1LBNCN	1.16		0.242
35	LE033	0.62	0.25	0.056
	E0pin	0.77	0.625	0.11
	F1LBNCN	0.92		0.205

VR spread
(Maisheev simulation)

Beam halo dispersion
(seen in E853)

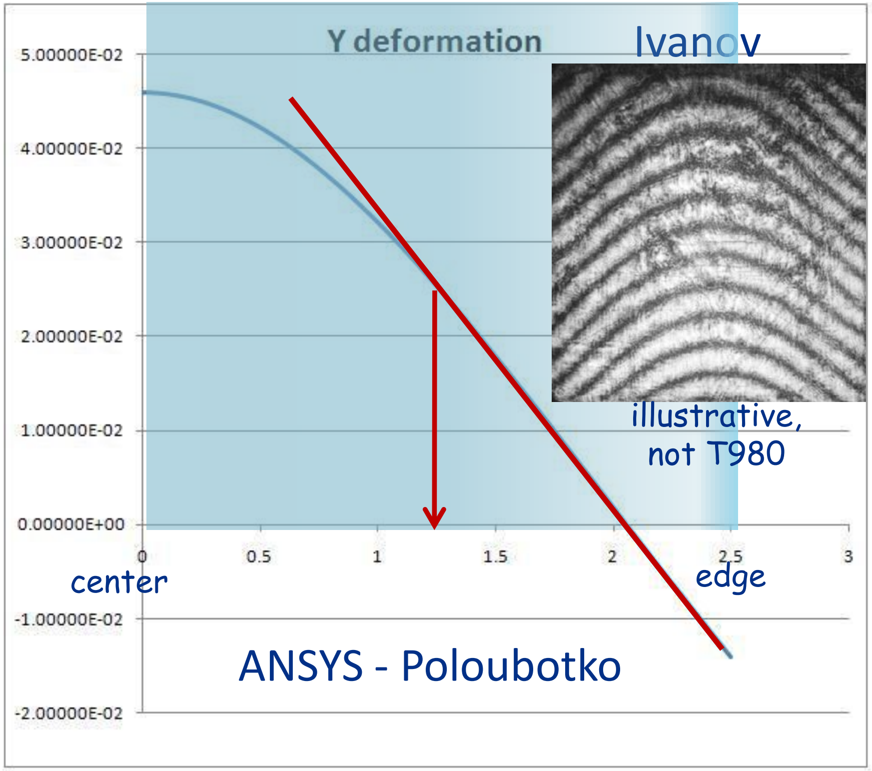
Multiple turn effects
(Drozhdin)

Crystal distortions

fringe – O(micron distortion)

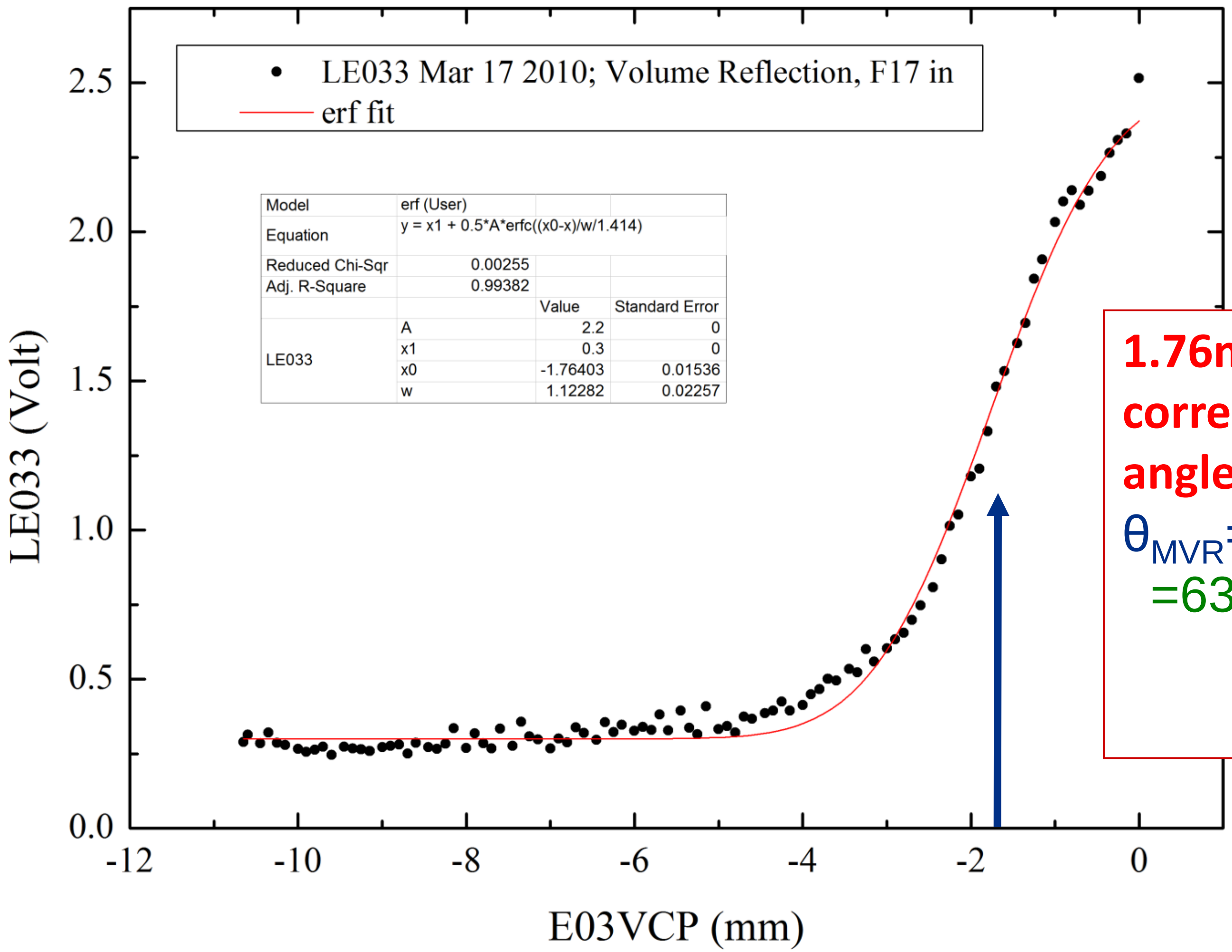
skew effects

Crystal distortions (O-shaped)



Fermilab

VR



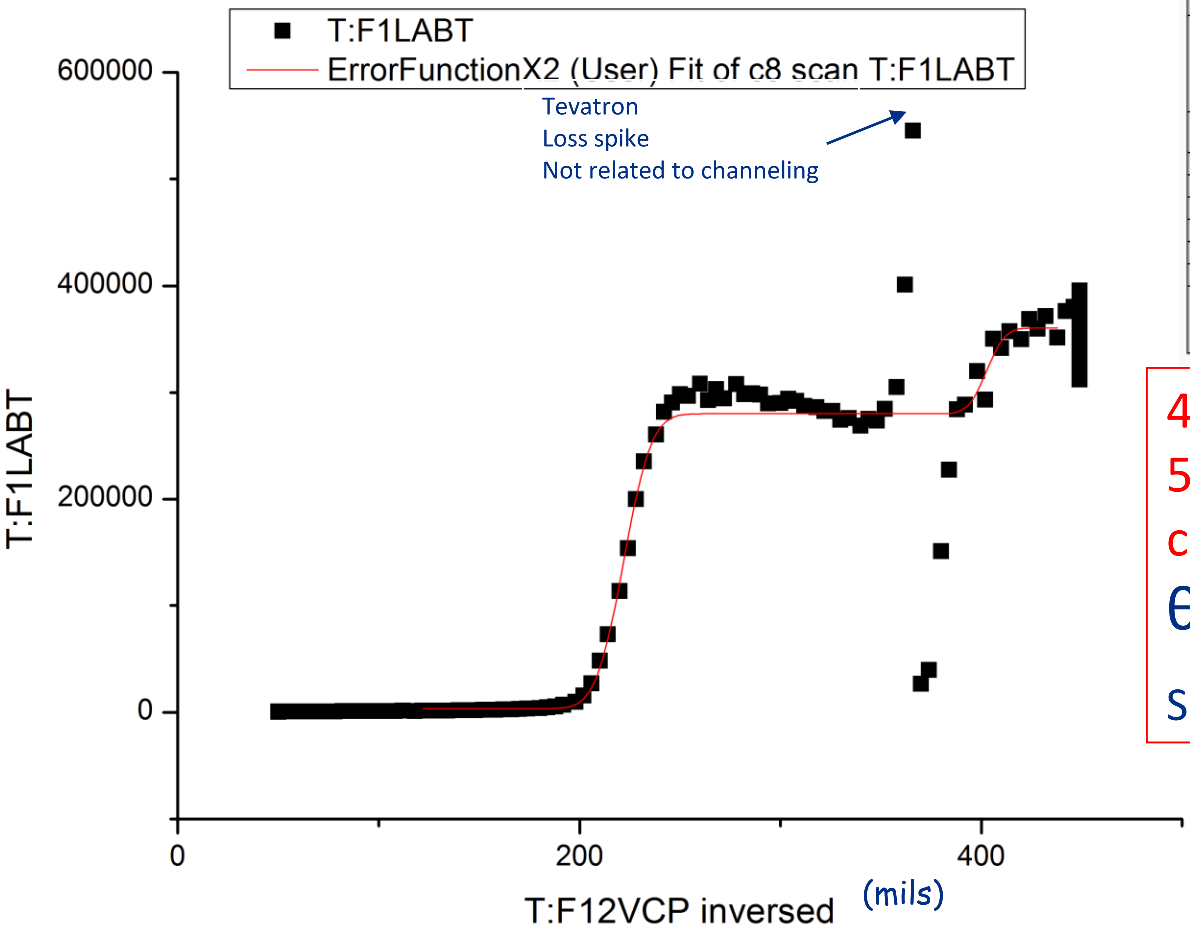
(MS-08-09)

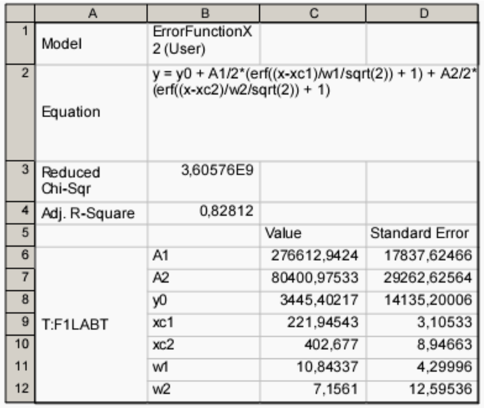
1.76mm displacement corresponds to VR angle:

θ_{MVR}=1.76mm/28m

=63 urad

CH





	A	B	C	D
1	Model	ErrorFunctionX2 (User)		
2	Equation	y = y0 + A1/2*(erf((x-xc1)/w1/sqrt(2)) + 1) + A2/2*(erf((x-xc2)/w2/sqrt(2)) + 1)		
3	Reduced Chi-Sqr	3,60576E9		
4	Adj. R-Square	0,82812		
5			Value	Standard Error
6	T:F1LABT	A1	276612,9424	17837,62466
7		A2	80400,97533	29262,62564
8		y0	3445,40217	14135,20006
9		xc1	221,94543	3,10533
10		xc2	402,677	8,94663
11		w1	10,84337	4,29996
12		w2	7,1561	12,59536

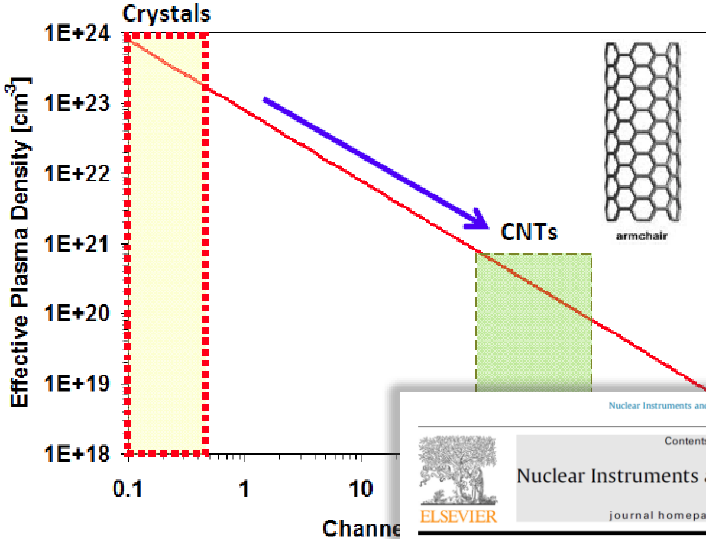
449-222mils/40mils/mm = 5.7 mm displacement from core for Channeled beam.

θ_{CH}= 186 urad

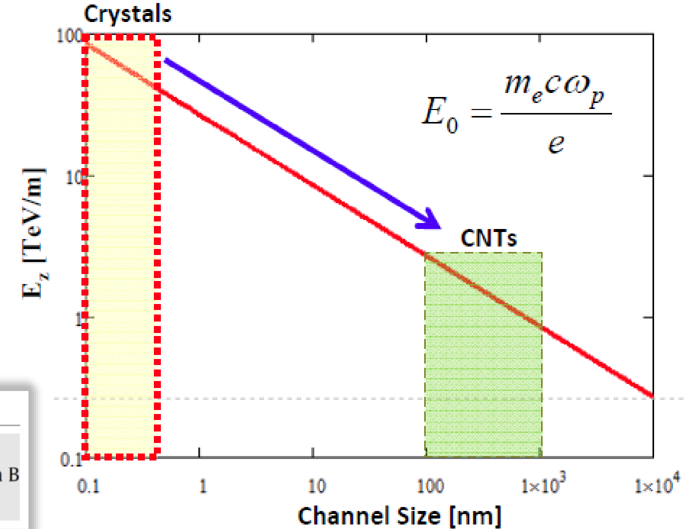
Specified θ_{CH} =200urad

Y.M.Shin et al: CNT vs Xtals

- Effective Plasma Density



- Acceleration Gradient



Nuclear Instruments and Methods in Physics Research B 355 (2015) 94–100

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TeV/m nano-accelerator: Investigation on feasibility of CNT-channeling acceleration at Fermilab

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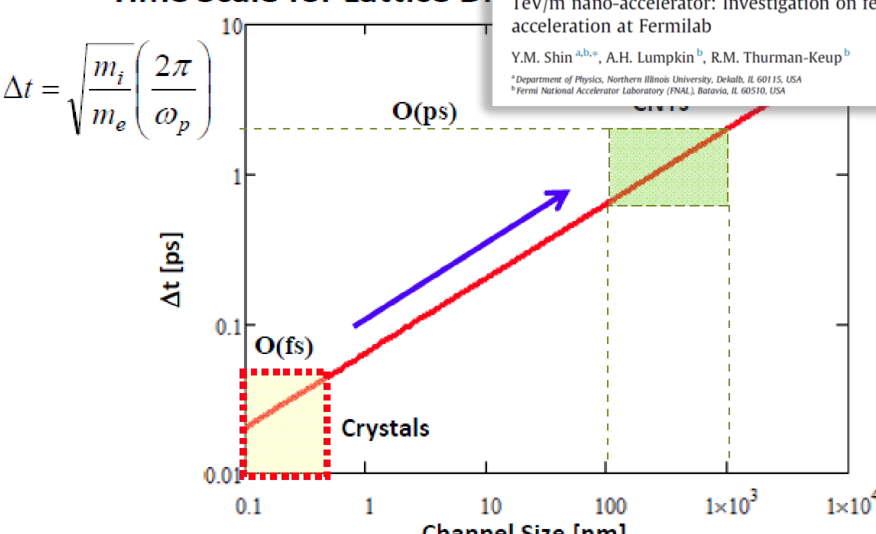
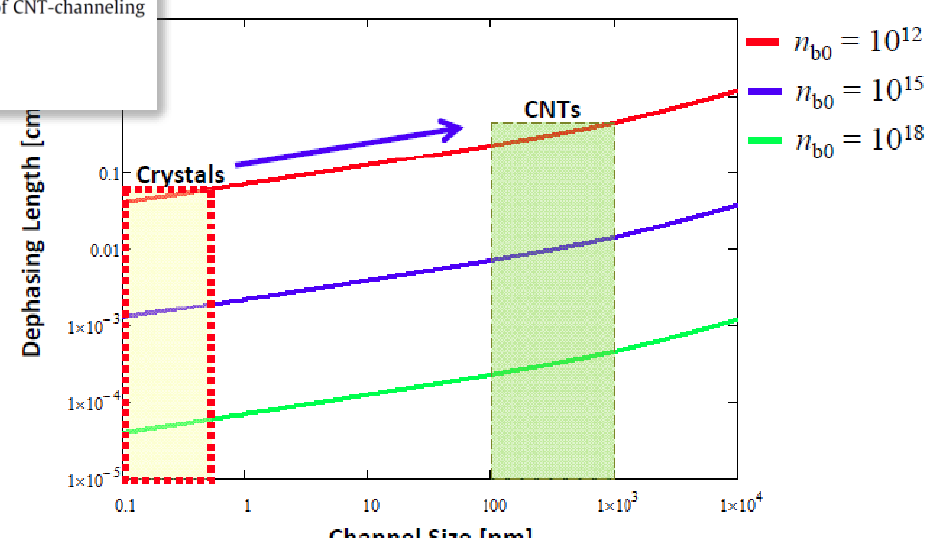
- Time Scale for Lattice Di



sing Length**



Fermilab