Crystal extraction – checkmarks and challenges

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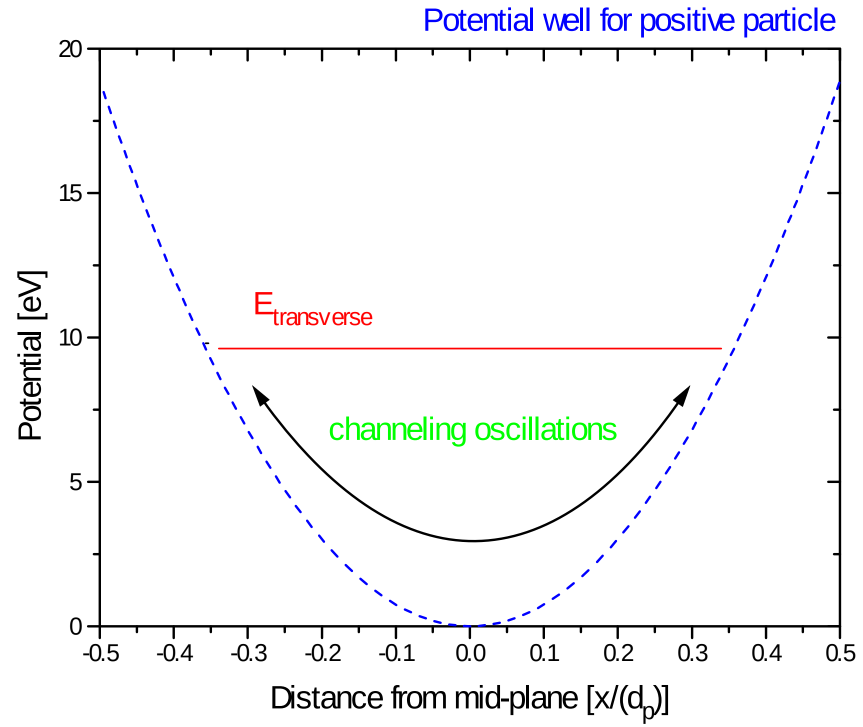
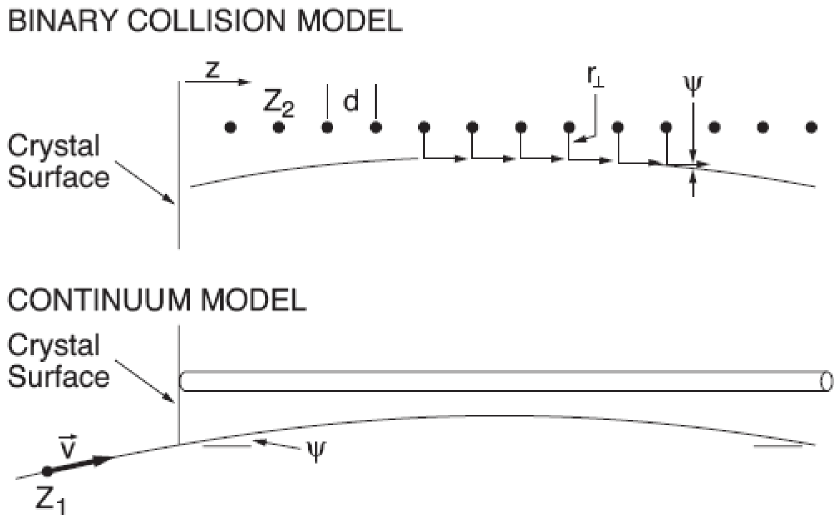
Introduction

Strong fields from screened nuclei, Continuum approximation

⇓

Strong fields with macroscopic extension





• $\psi_c = (2U/pv)^{1/2}$

Channeling in a curved crystal (I)

Centrifugal term

$U_{eff} = U(x)+U_{cf}$

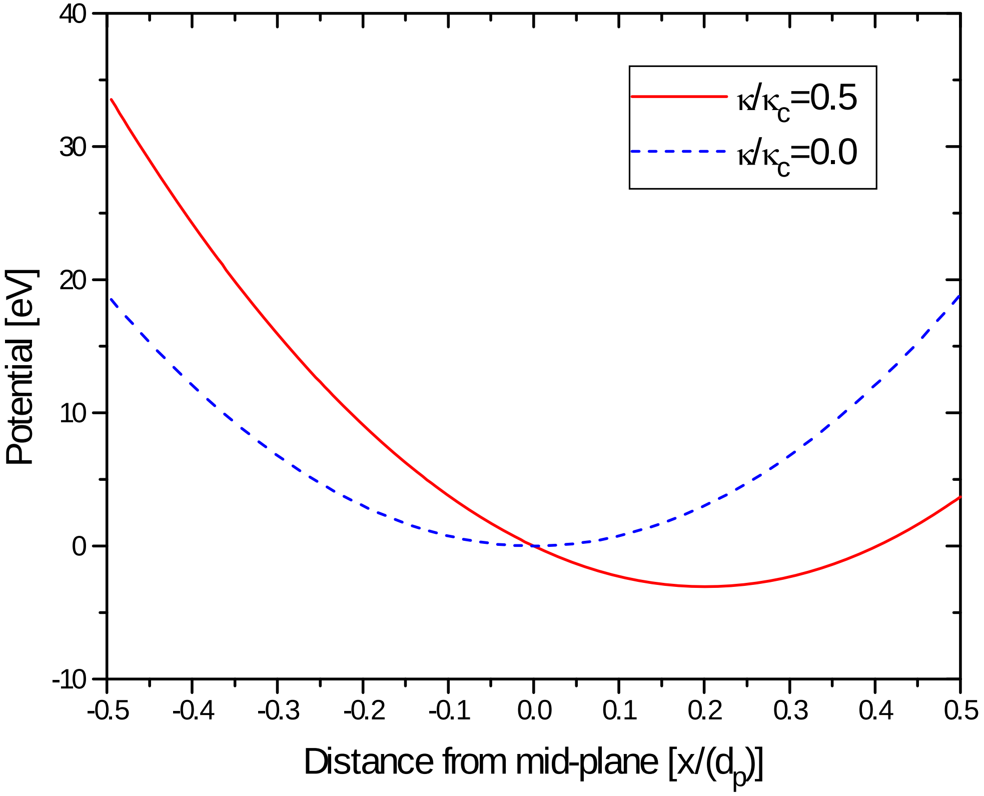
$= U(x) - pv\kappa x$

Curvature, κ=1/R

Well 'disappears':

$\kappa_c = \pi Z_1 Z_2 e^2 N d_p/pv$

$\kappa_c \propto Z_2/pv$



Channeling in a curved crystal (II)

Channeling oscillation wavelength: λ

$\theta(\lambda)<\psi \Leftrightarrow \kappa < \kappa_c = \pi Z_1 Z_2 e^2 N d_p / pv$

or

'Adiabatic condition':

- Deflect less than the critical angle over one oscillation

$\psi \propto (Z_1 Z_2/pv)^{1/2}$, $\lambda \propto 1/\psi \propto (pv/Z_1 Z_2)^{1/2}$

$\Downarrow$

$\kappa_c \propto Z_1 Z_2/pv$

(no difference apart from nucl. int. between protons and ions of same p/Z, high-Z materials preferred)

Dechanneling

Multiple Coulomb scattering $\Rightarrow$ dechanneling

Dechanneling length:

$L_D \approx 0.9$ m·p[TeV/c], Si (110)

$N = N_0 \exp(-x/L_D)$

Mechanical bending to $\approx$ 10 mrad

$\Downarrow$

High energies ($\geq$few GeV)

Structural bending possible with much smaller R

– crystal undulator, MeV bending

Dechanneling in a curved crystal (I)

Curvature dechanneling

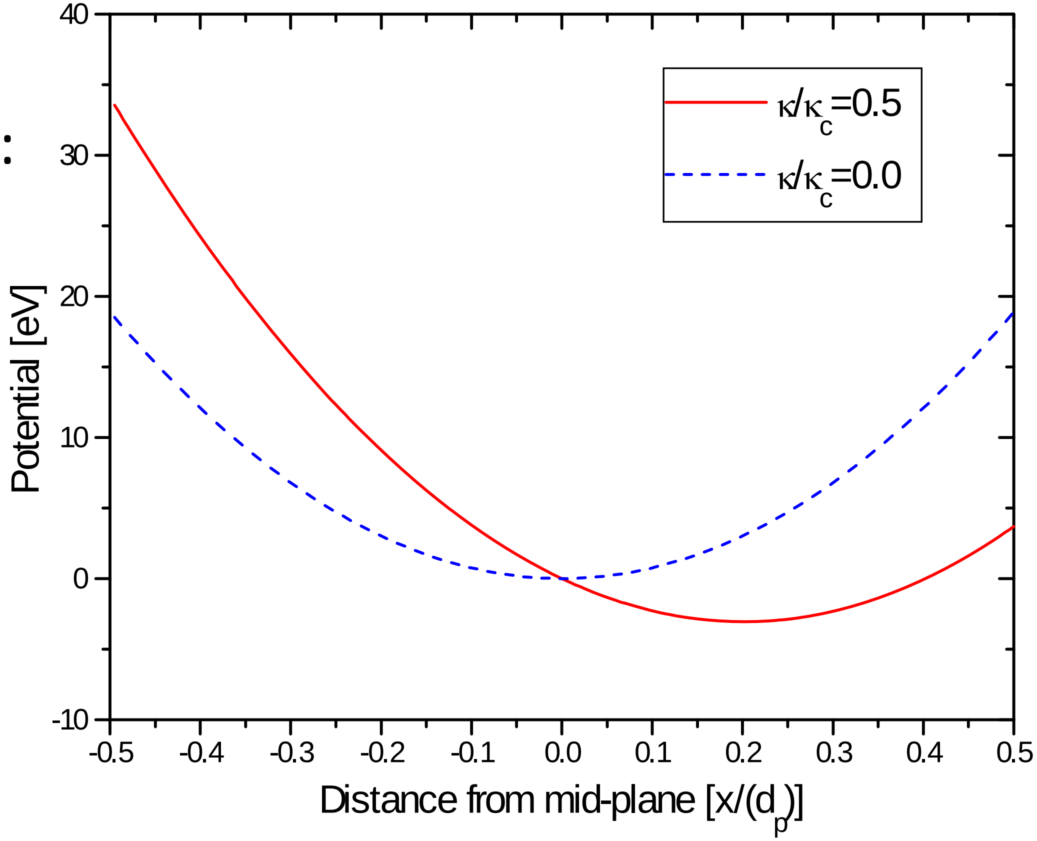
Decreased potential barrier:

$E_{depth}(\kappa)=E_{depth}(0)\ (1-\kappa/\kappa_c)^2$

Dechanneling fraction

$F \approx 3\kappa/\kappa_c$

(1-F) of phase-space stays channeled



Dechanneling in a curved crystal (II)

Multiple scattering dechanneling

Centrifugal term $\Rightarrow$

Equilibrium near nuclei

$\Downarrow$

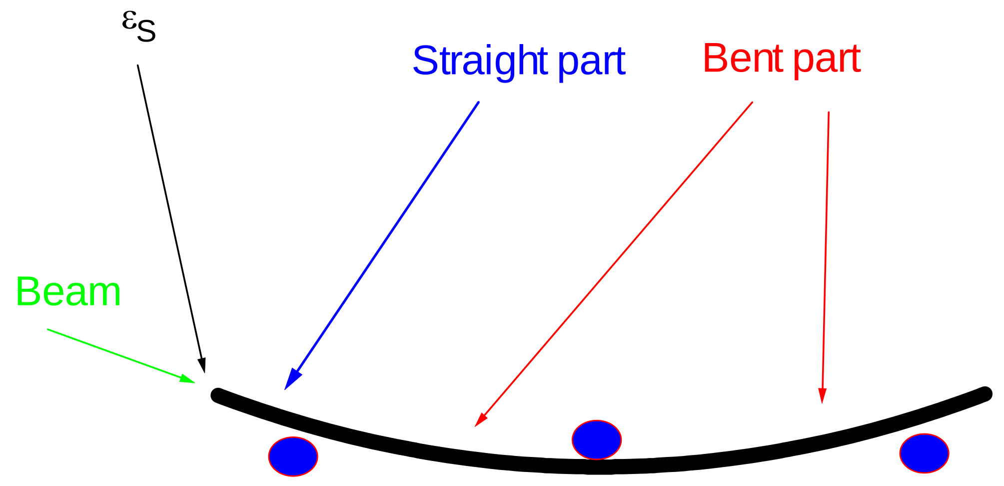
Decreased dechanneling length:

$L_D \propto E_{depth} \propto (1-\kappa/\kappa_c)^2 \approx (1-F/3)^2$

$$L_D(F)=L_D(0)(1-F/3)^2$$

Model for deflection efficiency

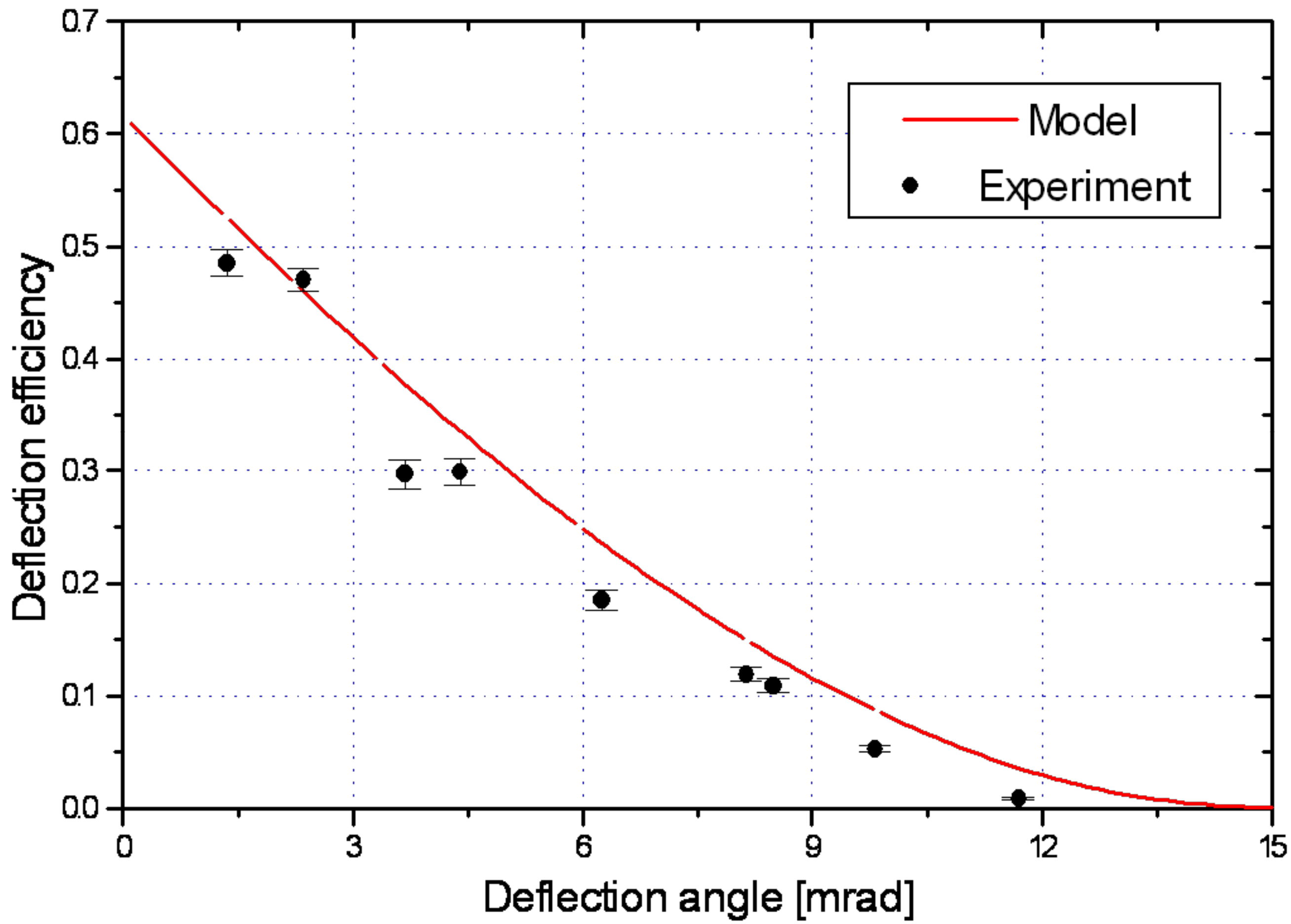
$$\varepsilon = \varepsilon_S \cdot \exp(-L_S/L_D) \cdot \exp(-L_B/L_D(1-F/3)^2) \cdot (1-F)$$



Three point bender

First extensive investigation at SPS

Si (111), 450 GeV protons



Heavy materials

Theoretical expectation:

Higher *Z*, Higher field, $L_D\kappa_c \propto Z_2$

$L_D\kappa_c$=0.3, Si (110), weak energy dependence

At optimal length: $\varepsilon \approx \varepsilon_S(1-(3\theta/ L_D\kappa_c)^{1/2})^2$

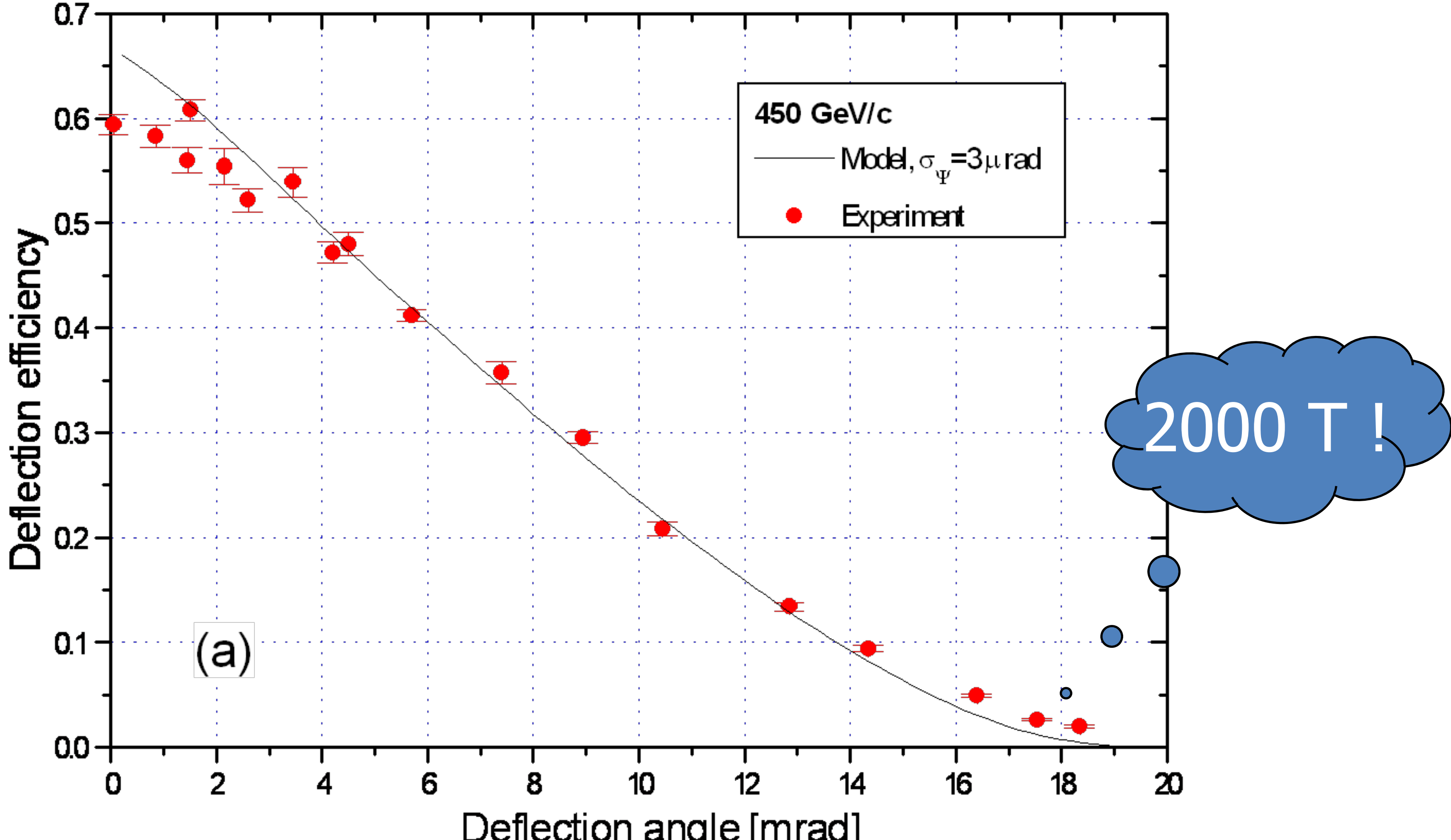
- Higher $L_D\kappa_c \Rightarrow$ higher efficiency for fixed θ

Silicon (Z=14) in good agreement with model

How about germanium (Z=32)?

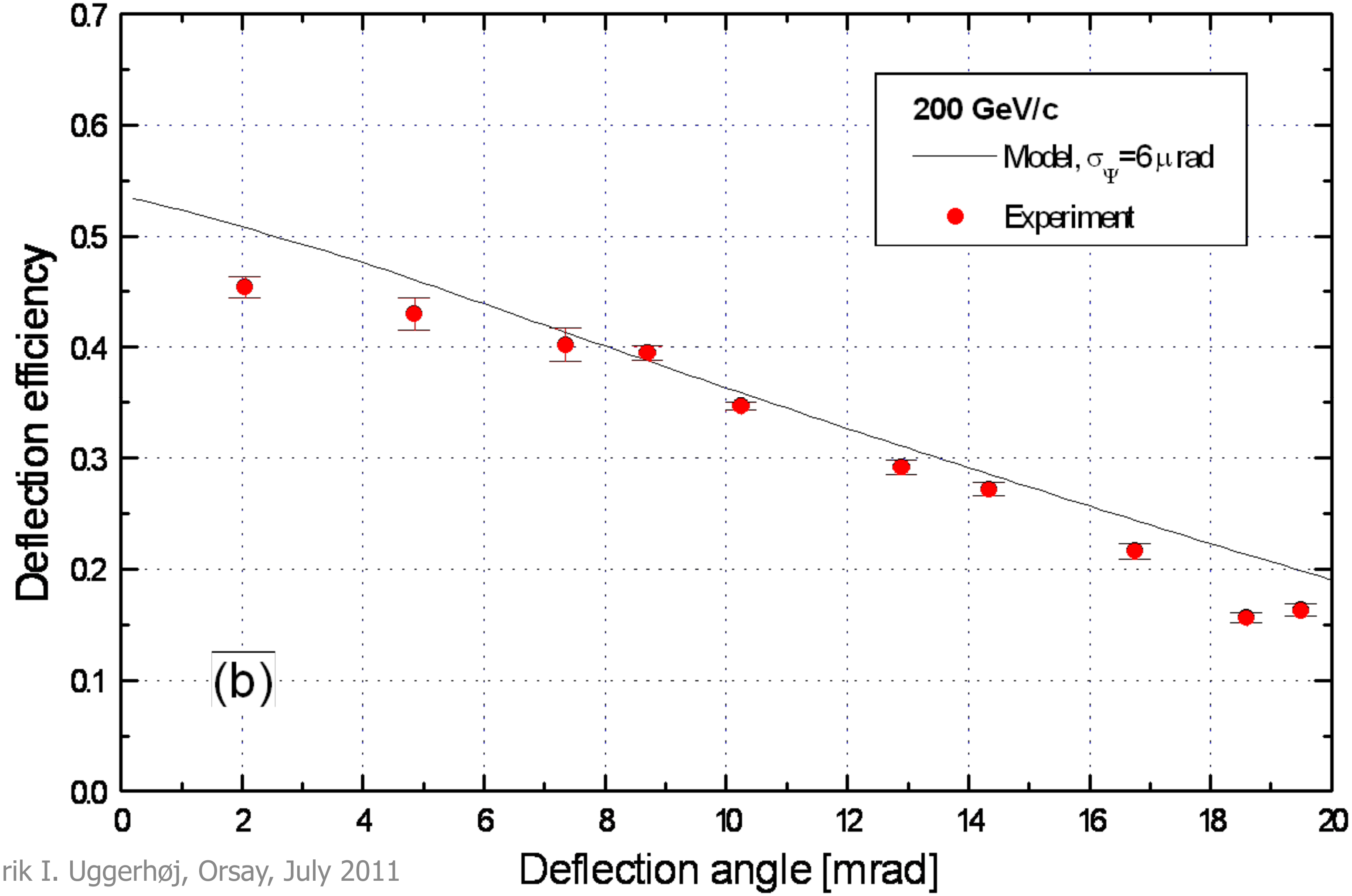
Higher Z

Ge (110), 450 GeV protons



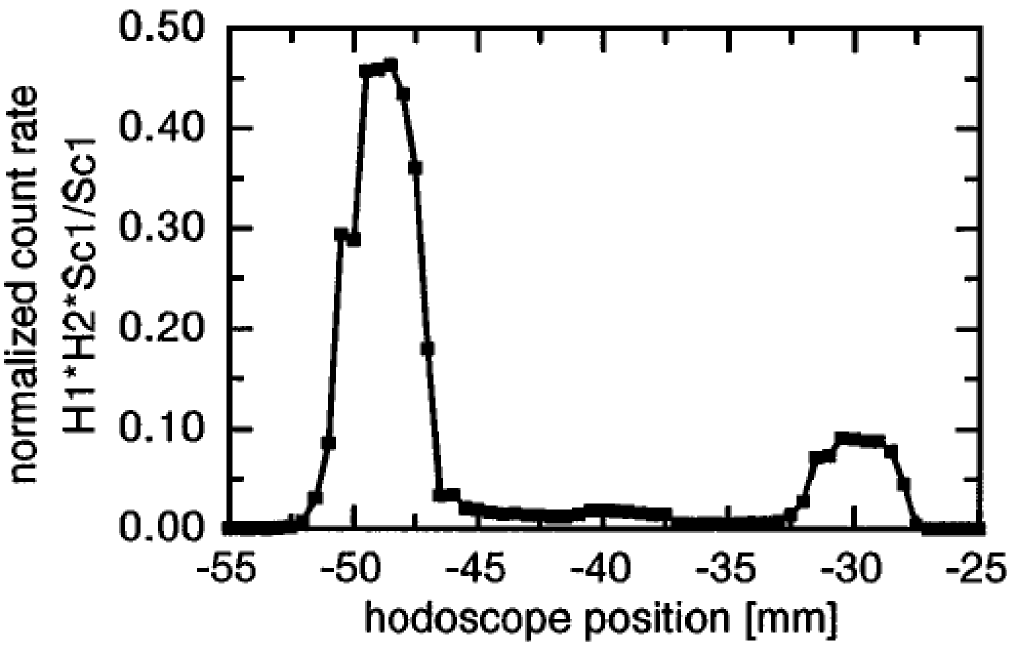
Energy dependence

Germanium (110), 200 GeV p^+ and π^+

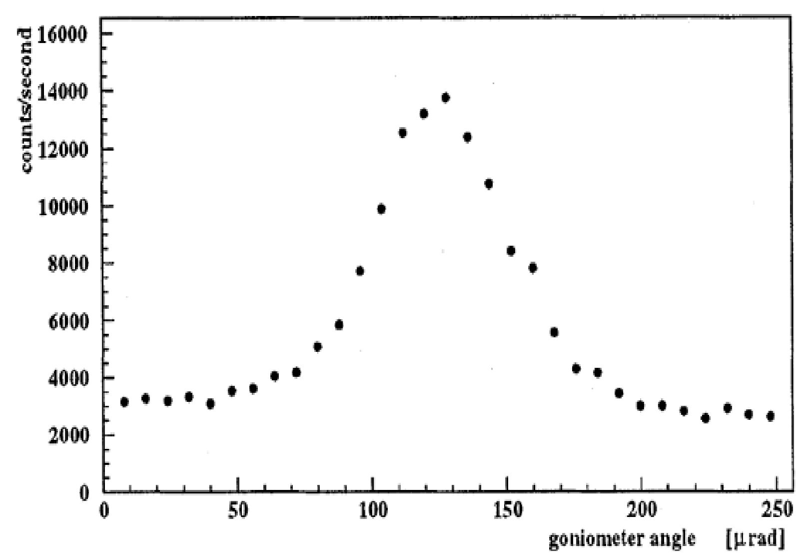


Heavy nuclei

33 TeV Pb^{82+} deflection (as for protons)

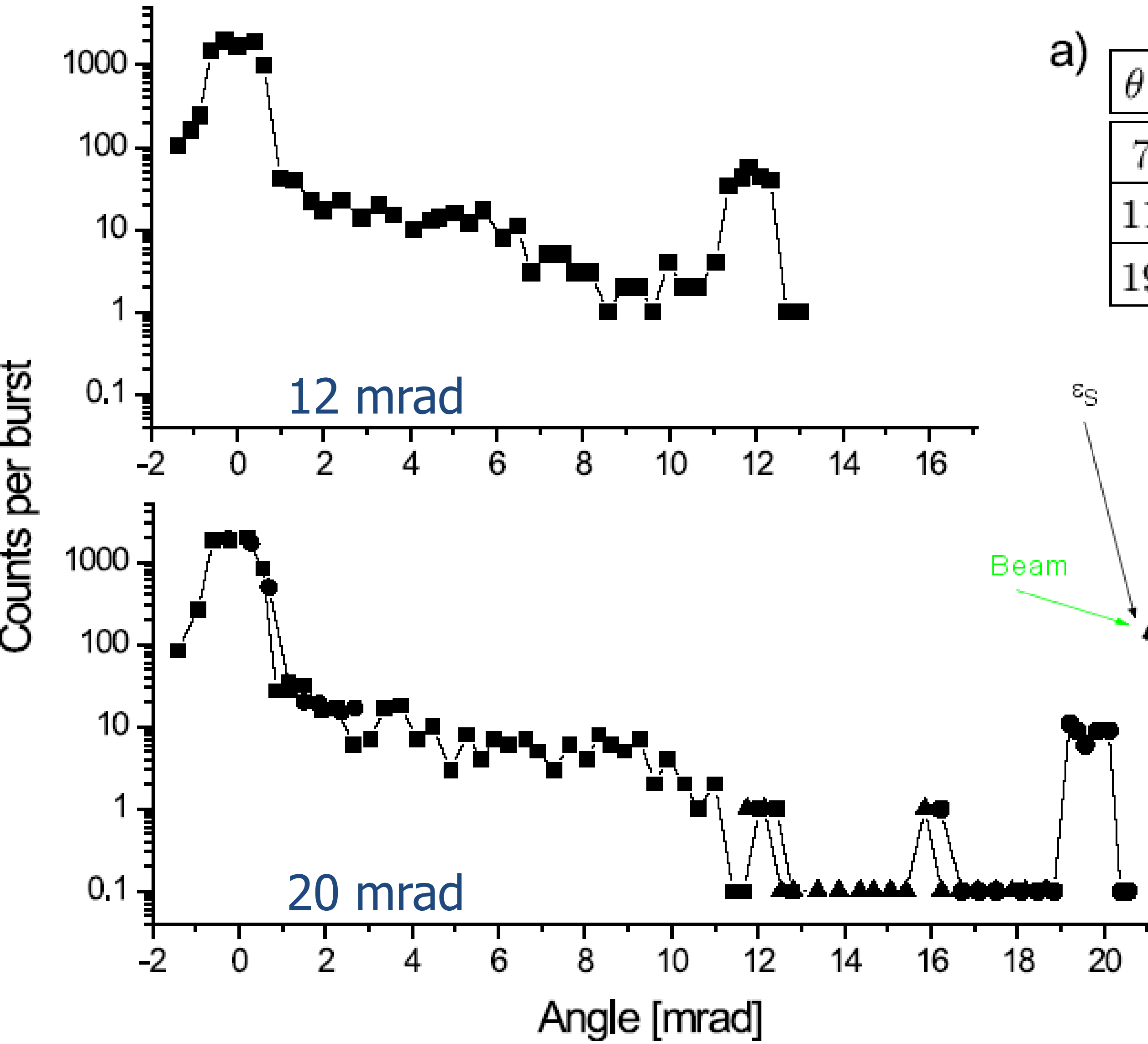


22 TeV Pb^{82+} extraction (10% eff., factor 2 less than p+)



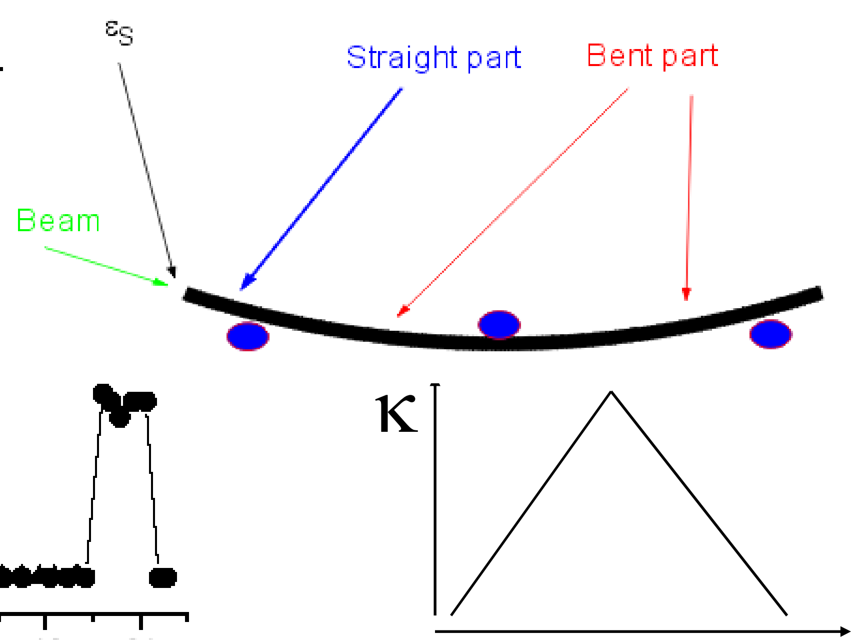
Small EM dissociation, nuclear interaction

Heavy ion deflection (In^{49+})



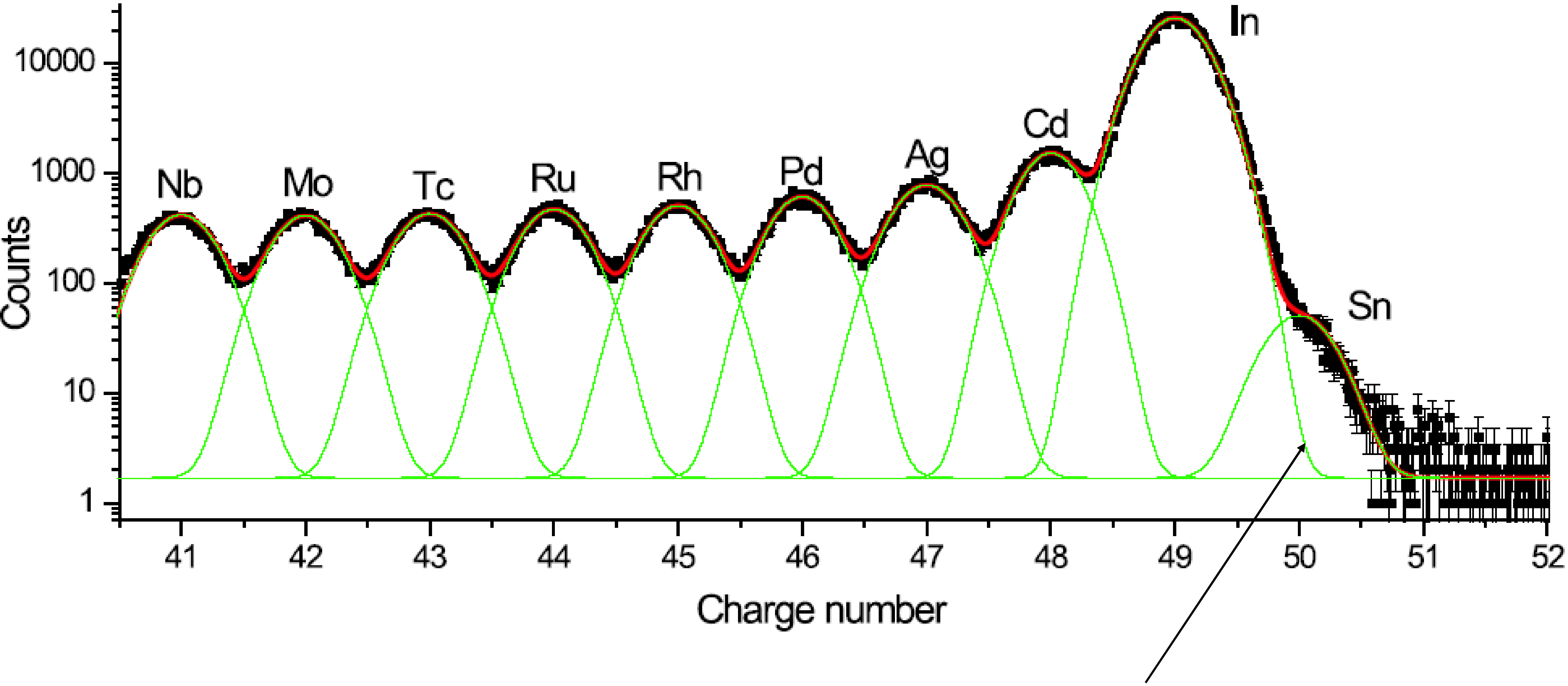
a)

θ [mrad]	$\sigma(\vartheta)$ [μrad]	ε [%]
7.5±0.3	34±1	3.0±0.2
11.9±0.2	35±1	2.0±0.1
19.8±0.2	26±7	0.4±0.1



Dechanneling for increasing curvature

Heavy ion deflection



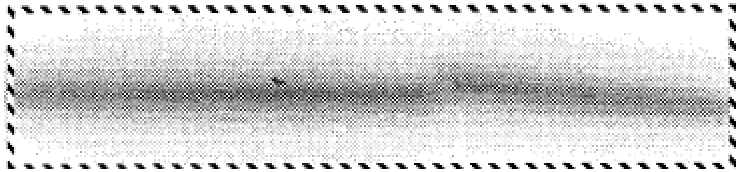
- Nuclear-charge pickup, $n+\gamma\rightarrow p+\pi^-$

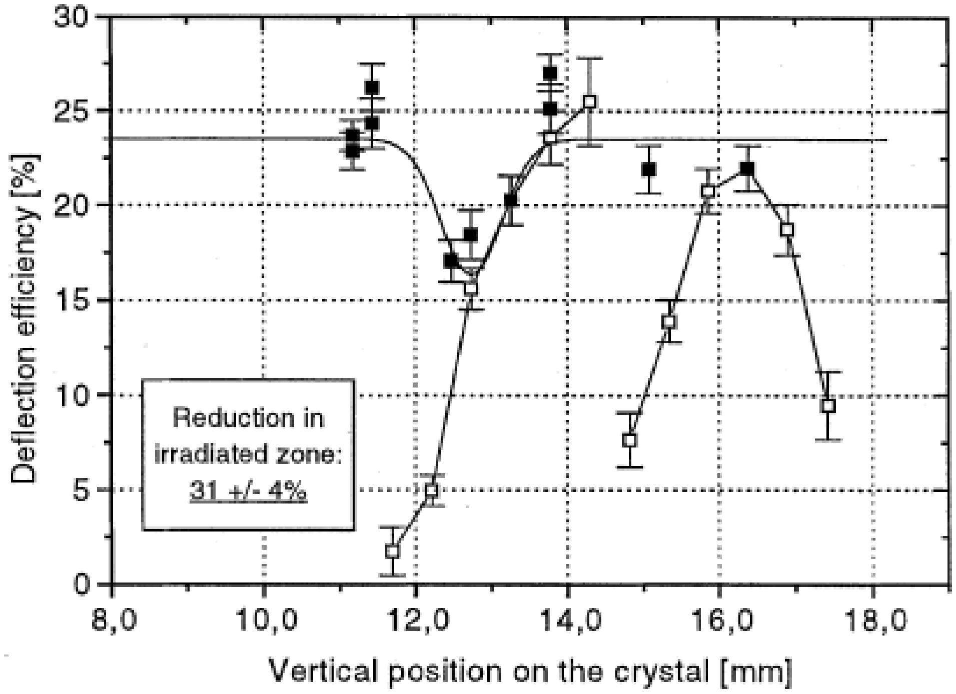
- Ions predominantly (≈99% for realistic thicknesses) exit in the same charge state as they enter

Radiation damage

A bent Si crystal was irradiated at SPS target station T2 for one year.

Peak fluence: $5 \times 10^{20} \ \ p^{+}/cm^{2}$





$6\% \ /10^{20} \ \ p^{+}/cm^{2}$

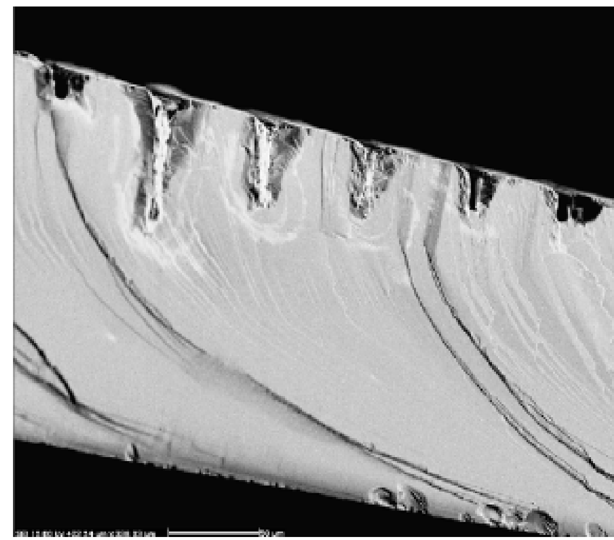
Bent diamonds

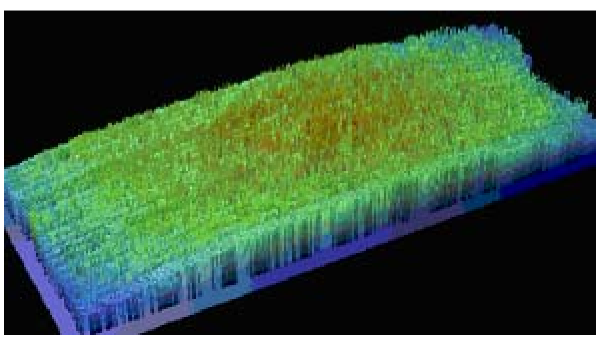
- Diamonds have been tested in SLAC FFTB: No visible damage!

Electron densities of the order $10^{21}\ \mathrm{cm}^{-3}$

Nuclear Instruments and Methods in Physics Research B 267 (2009) 2952–2957

Bending diamonds by femtosecond laser ablation





Curvature radius of approx. 1 m

Summary

Deflection phenomenon in bent crystal:

- Light material, Si, eff. up to 50%
- Heavy material, Ge, eff. up to 60%
- Dependence on curvature
- Energy dependence
- Radiation sensitivity (for protons, 6%/10^{20} p^+/cm^2)
- Nuclei, Pb^{82+}
- Nuclei, In^{49+}

Possible applications

- Extraction of p^+ or Pb from LHC
- Extraction of Au from RHIC

Heavy ions???
Only remaining 'big' exp. question for deflection in bent crystals

LHC – what's new?

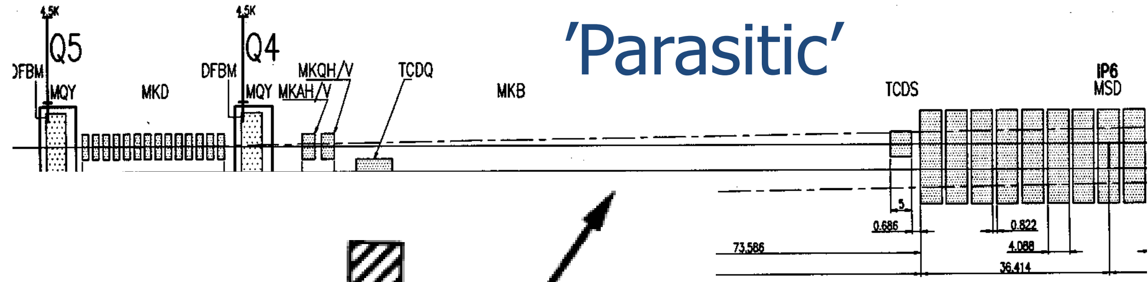
- …Since the LHB proposal

  LHCC/93-45:
  - Accelerator lattice
  - Twiss parameters (now known)
  - Warm and cold sections
  - Dump scheme
  - Beam parameters
  - Exact layout
  - Crystal radiation damage:

    10^{13} p^+/day, 10^{-5} cm^2 , limit in Si: 10^{20} p^+/cm^2 =>

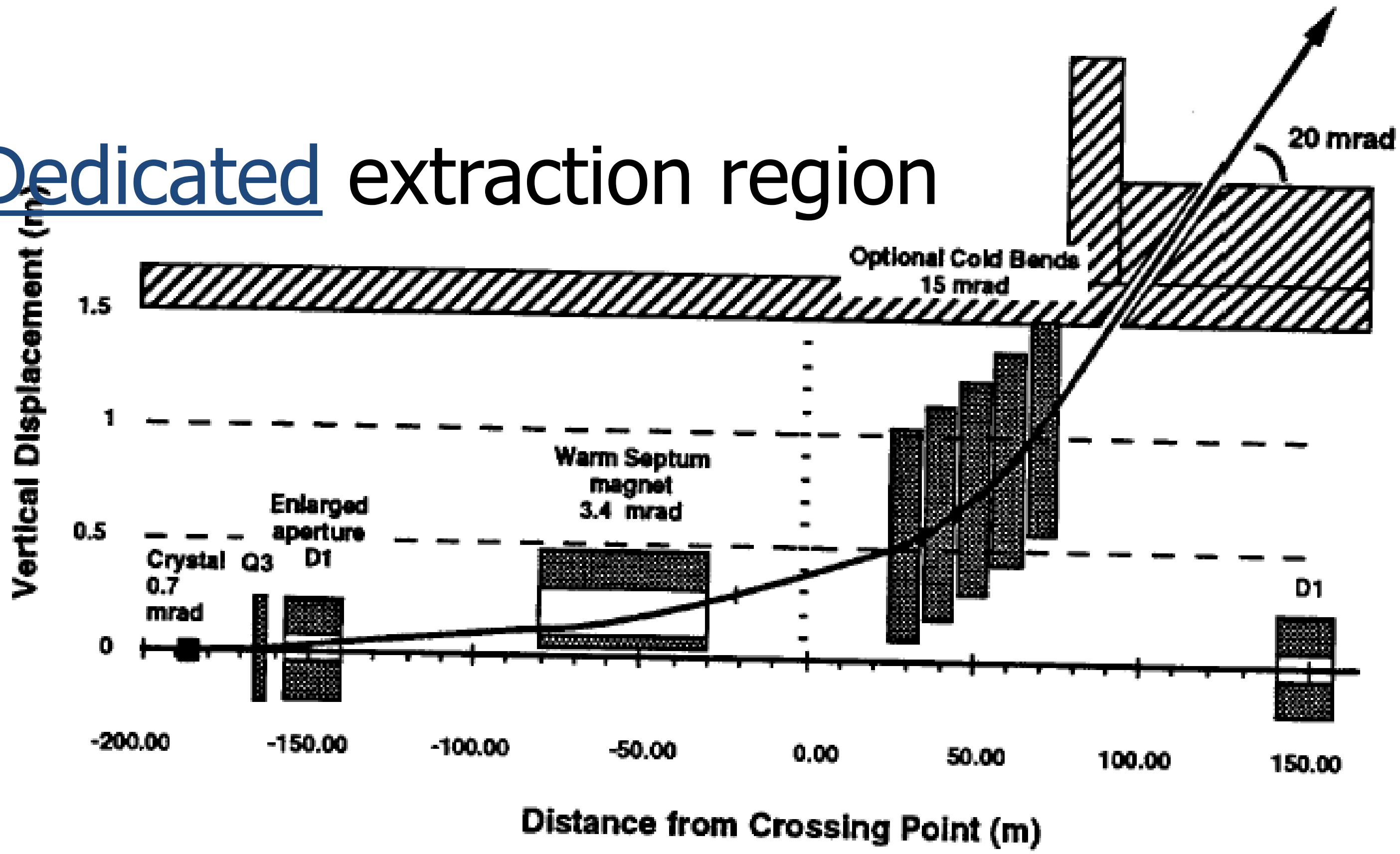
    about 100 days (then remote displacement, 0.1 mm)

    Probably insignificant in diamond



'Parasitic'

Dedicated extraction region



"… an even intersection" (RF, Dump, ALICE, LHC-B)

1. Accelerator lattice
2. Twiss parameters
3. Warm and cold sections
4. Dump scheme
5. Beam parameters
6. Exact layout
7. Technical drawings
8. Crystal radiation damage

with the halo protons. This effect has been studied in several laboratories and so far no evidence of degradation of channeling performance has been obtained, for fluences up to 10^{19}particles/cm^2. [7] It is expected that the true limit could be placed about three orders of magnitude above.

… true!

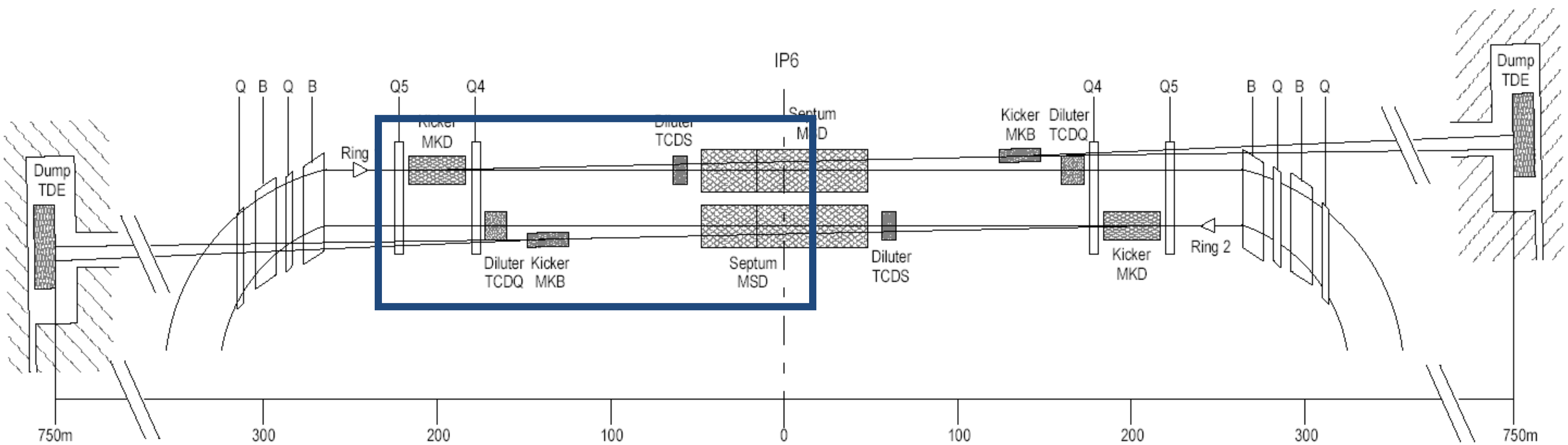
One possibility: LHC dump, IP6

Nuclear Instruments and Methods in Physics Research B 234 (2005) 31–39

www.elsev

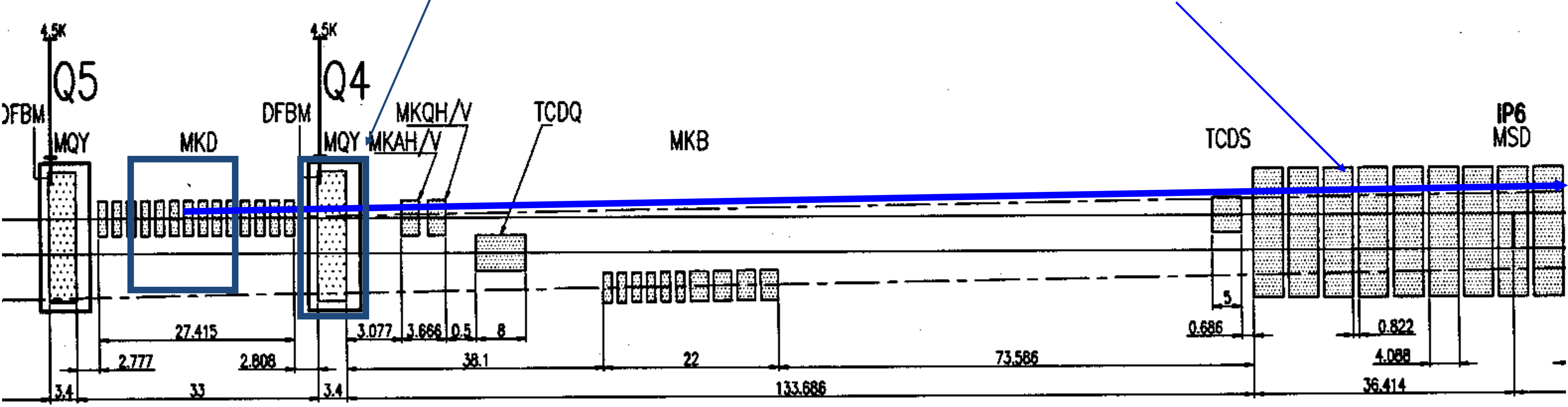
Strong crystalline fields – a possibility for extraction from the LHC

E. Uggerhøj, U.I. Uggerhøj *

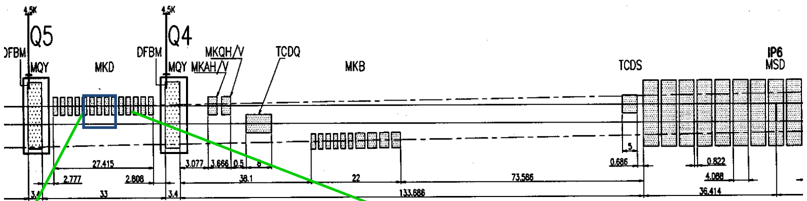


LHC dump, IP6

- Only cold section
- Extracted (dumped) beam



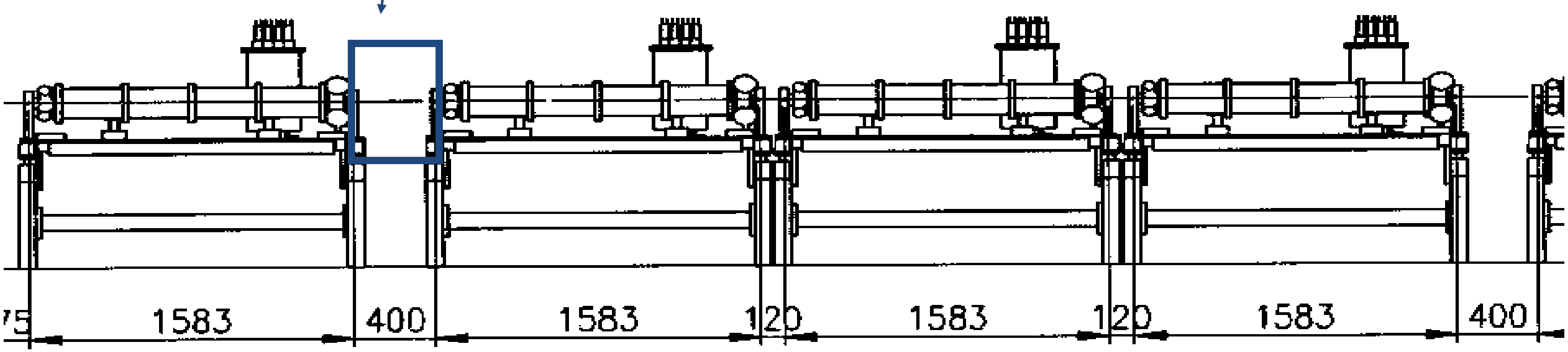
Kicker section, dump, IP6



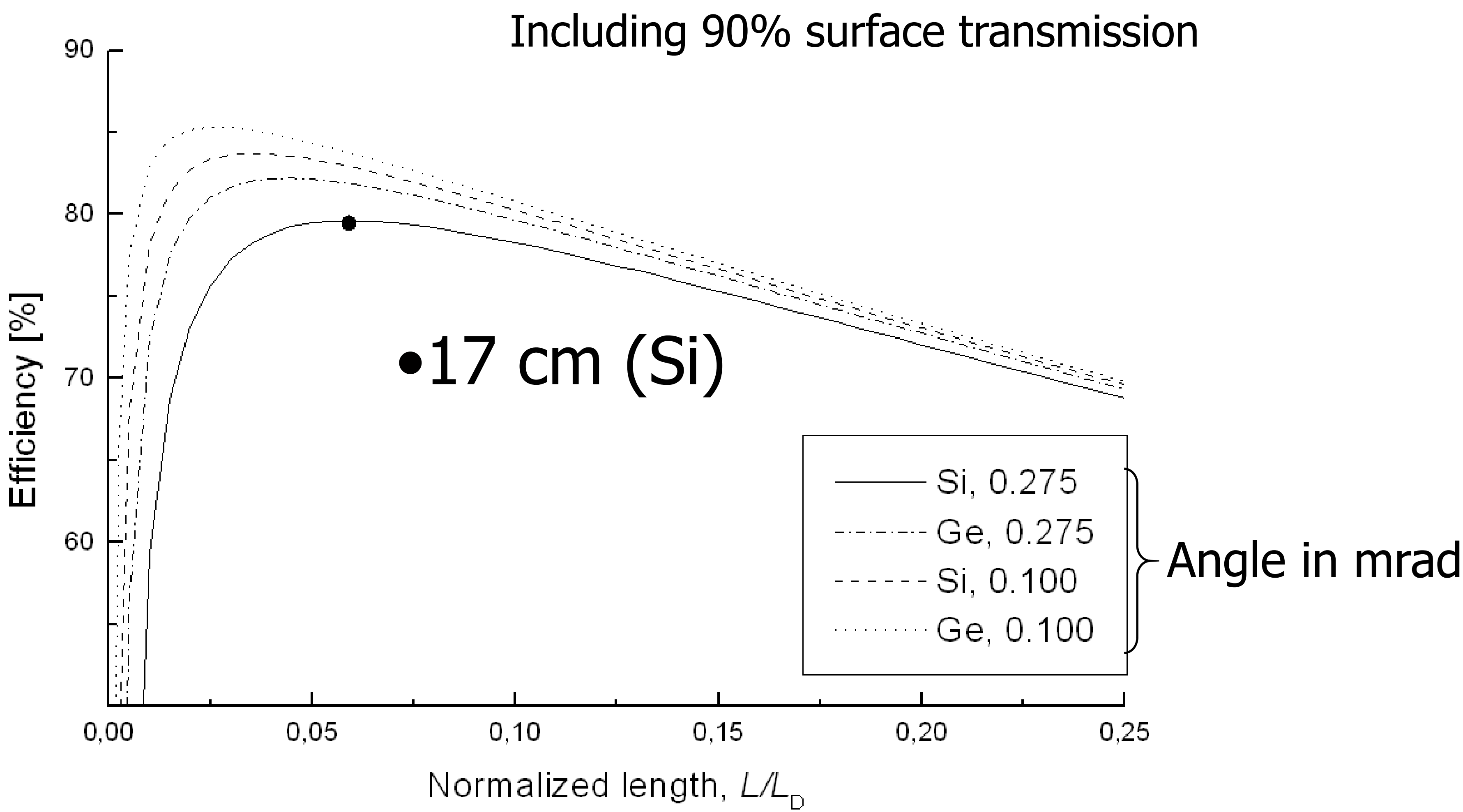
- Possible location of bent crystal(s)

- d_{IP6}=192710 mm
- β-function: appr. 200 m

MKD



Bending efficiency (single pass)



Multi-pass

ELSEVIER

14 September 1995

PHYSICS LETTERS B

Physics Letters B 357 (1995) 671–677

High efficiency multi-pass proton beam extraction with a bent crystal at the SPS

X. Altuna [b], M.P. Bussa [f], G. Carboni [e,1], B. Dehning [b], K. Elsener [b], A. Ferrari [b], G. Fidecaro [b], A. Freund [c], R. Guinand [b], M. Gyr [b], W. Herr [b], J. Klem [b,d], M. Laffin [b], L. Lanceri [g], U. Mikkelsen [a,b], S.P. Møller [a], W. Scandale [b], F. Tosello [f], E. Uggerhøj [a], G. Vuagnin [b,g], E. Weisse [b], S. Weisz [b]

[a] *ISA, University of Århus, Aarhus, Denmark*

[b] *CERN, Geneva, Switzerland*

[c] *ESRF, Grenoble, France*

[d] *HTI, Helsinki University of Technology, Helsinki, Finland*

[e] *Università di Pisa and INFN, Pisa, Italy*

[f] *Università di Torino and INFN, Torino, Italy*

[g] *Università di Trieste and INFN, Trieste, Italy*

- Multi-pass: Shorter crystals (Biryukov *et al.*)

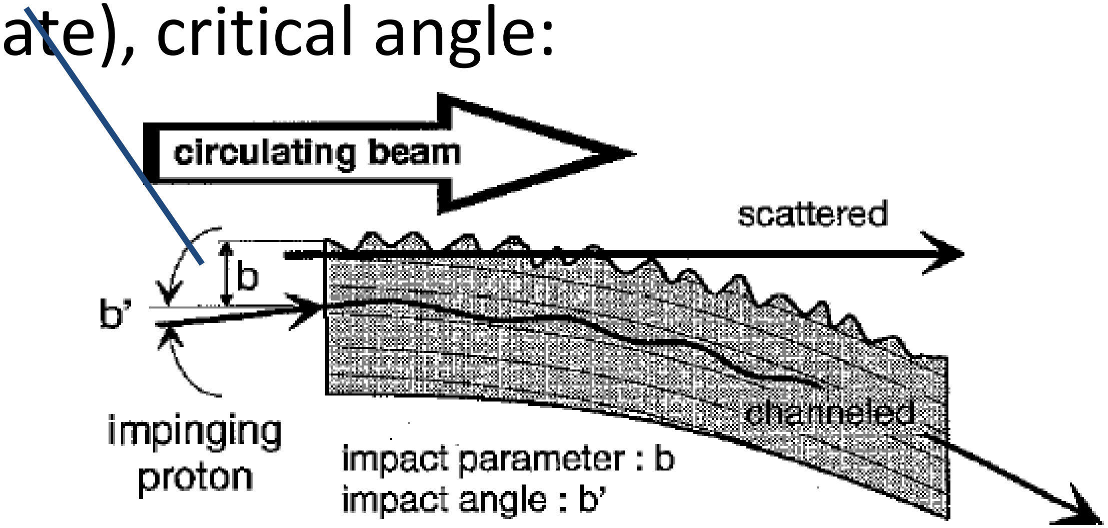
What do we get?

- Beam loss from LHC: about 10^9 p^+/s
- Assuming efficiency in multi-pass mode 50%
- $5 \cdot 10^8$ p^+/s, $\sqrt{s}$ = 115 GeV
- Likely impact parameters on the crystal: about 10 μm (difficult estimate), critical angle:

  2 μrad =>

  emittance (v):

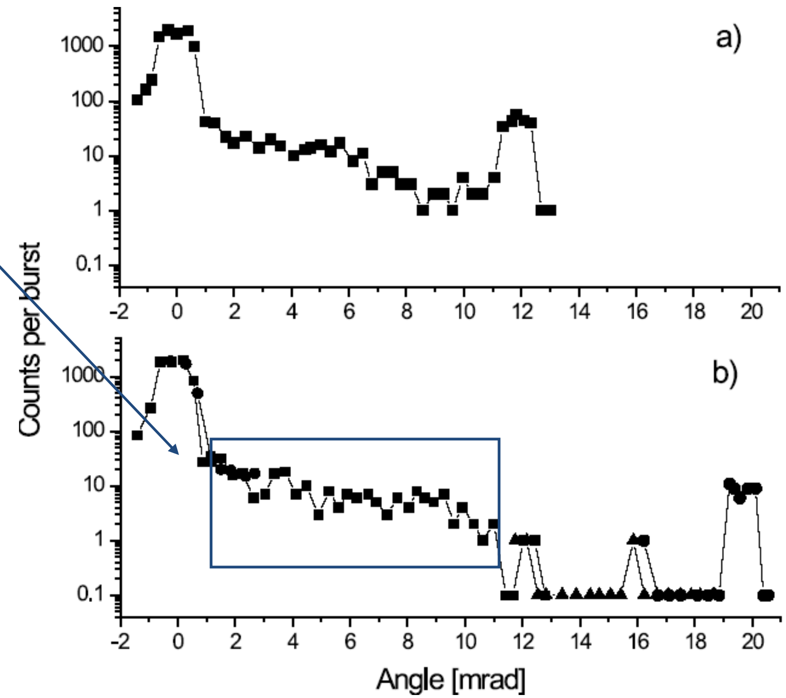
  $20 \cdot 10^{-6}$ mm · mrad



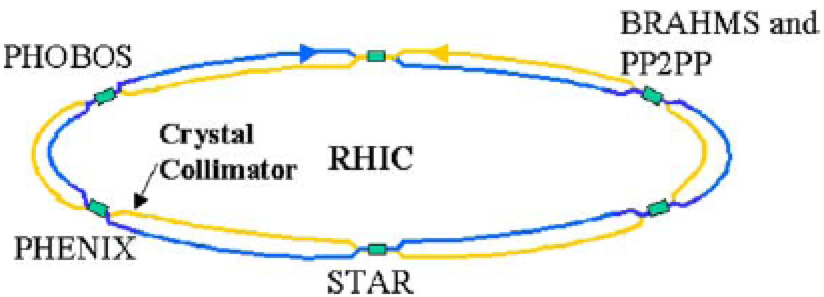
- Extremely small emittance
- Beam size at dump (in extraction direction): 0.3 mm

Possible problems (and possible solutions)

- Dechanneling losses in regions of increasing curvature (ZnO coating on first few mm)
- Heavy ion radiation damage to crystal?
- High-intensity beam during dump (fast dipole)

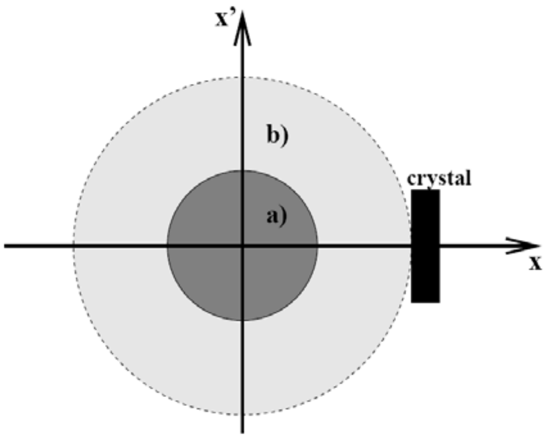


Recent developments - RHIC



'Smart collimation'

R.P. Fliller III et al. / Nucl. Instr. and Meth. in Phys. Res. B 234 (2005) 47–56



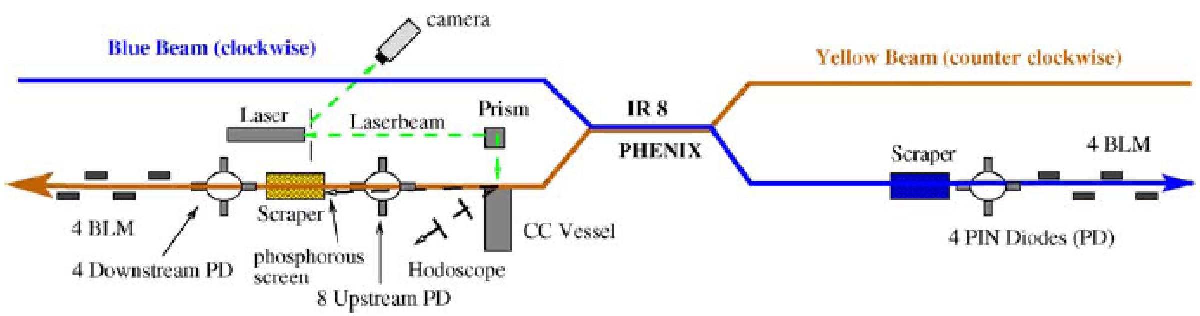
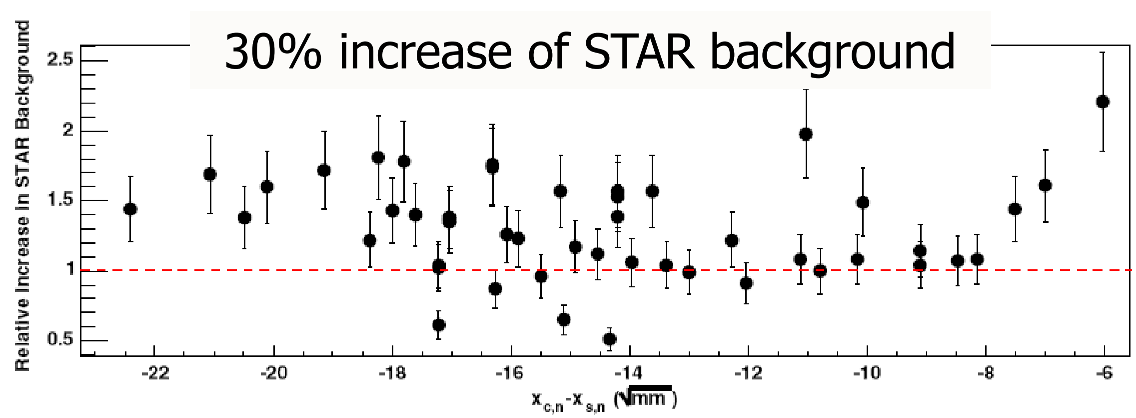


Fig. 2. RHIC collimation system.



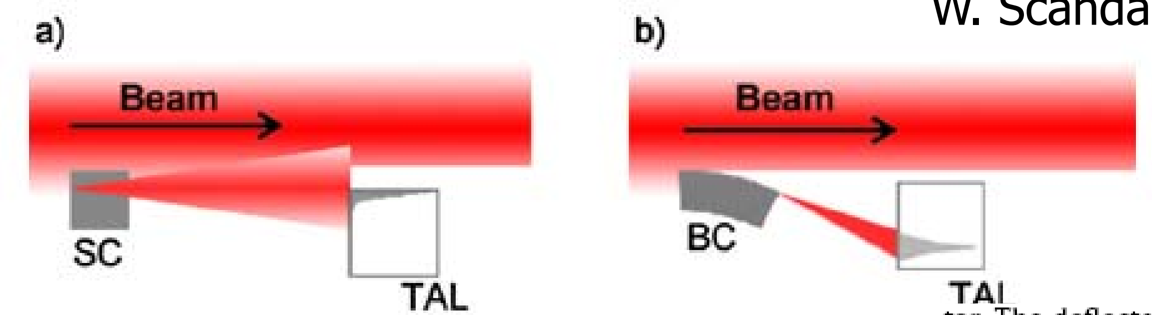
Important to have the crystal at the correct lattice phase (small spread of angles)

Recent developments – CERN SPS

Physics Letters B 692 (2010) 78–82

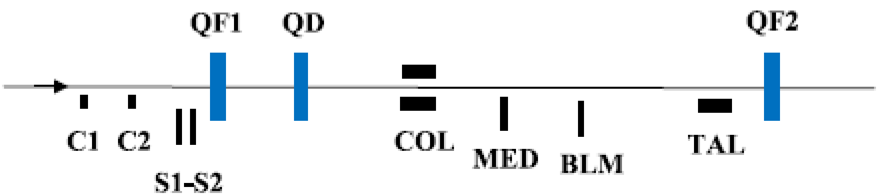
First results on the SPS beam collimation with bent crystals

W. Scandale *et al.*



$\theta_k = -173\ \mu\text{rad}.$

tor. The deflected beam profiles measured with the collimator scan showed that the deflection efficiency of halo protons in channeling states was $(75 \pm 4)\%$ and $(85 \pm 5)\%$ for the strip and quasi-mosaic



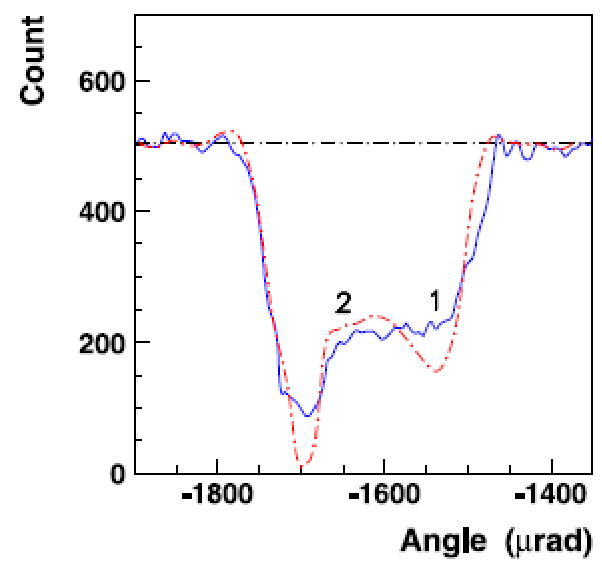


Fig. 3. (Color online.) (1) The dependence of the S1–S2 telescope count on the angular position of the crystal 1; (2) The dependence of the number of inelastic nuclear interactions of protons in the crystal on its orientation angle obtained by simulation. The dot-dashed line shows the level of the beam losses for the amorphous orientation of the crystal.

Heavy ions have lately also been investigated

Additional advantages

- Deflection *angle* (not eff.) independent on energy:
  - Extraction possible at any energy 0.450-7 TeV
  - (Smart) collimation, in particular for heavy ions
  - Beam stability – extracted beam intensity
  - Beam monitoring

  - Polarization (?)

Polarized beams (?)

V.M. Samsonov/Nucl. Instr. and Meth. in Phys. Res. B 119 (1996) 271–279

Spin precession

$$\Theta_b = \beta H L/p,$$

$$\Theta_s = \Theta_b \gamma (g-2)/2,$$

$$\Theta_c = l/R_0,$$

$$\Theta_s = \gamma \Theta_c (g-2)/2.$$

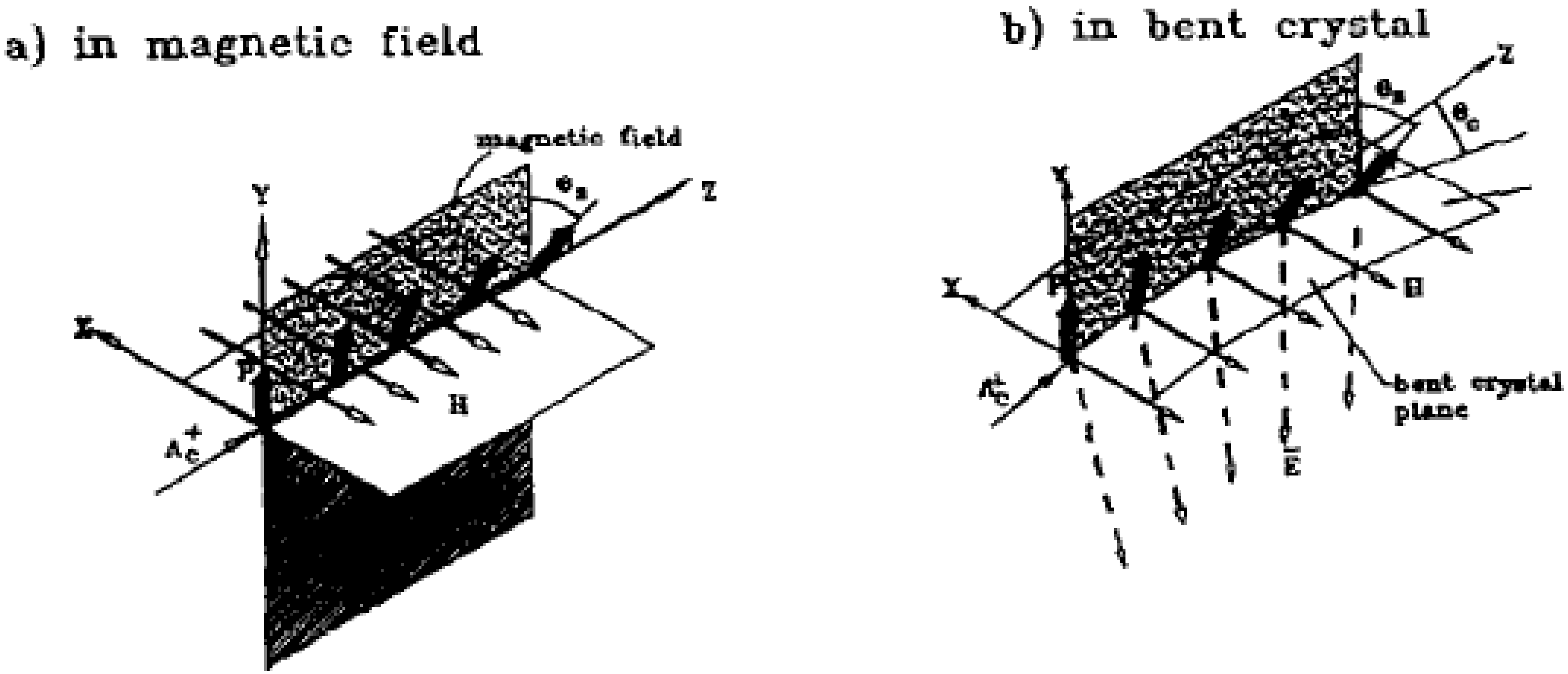


Fig. 4. Schematic illustration of spin precession in: (a) magnetic field; (b) bent crystal.

Polarized beams (?)

V.M. Samsonov/Nucl. Instr. and Meth. in Phys. Res. B 119 (1996) 271–279

Spin precession

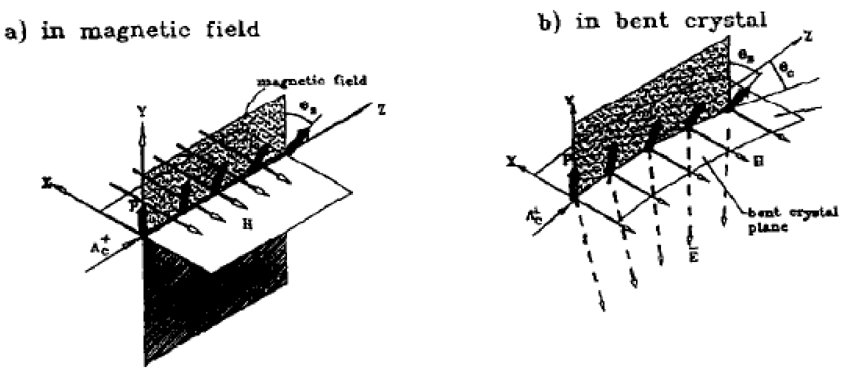


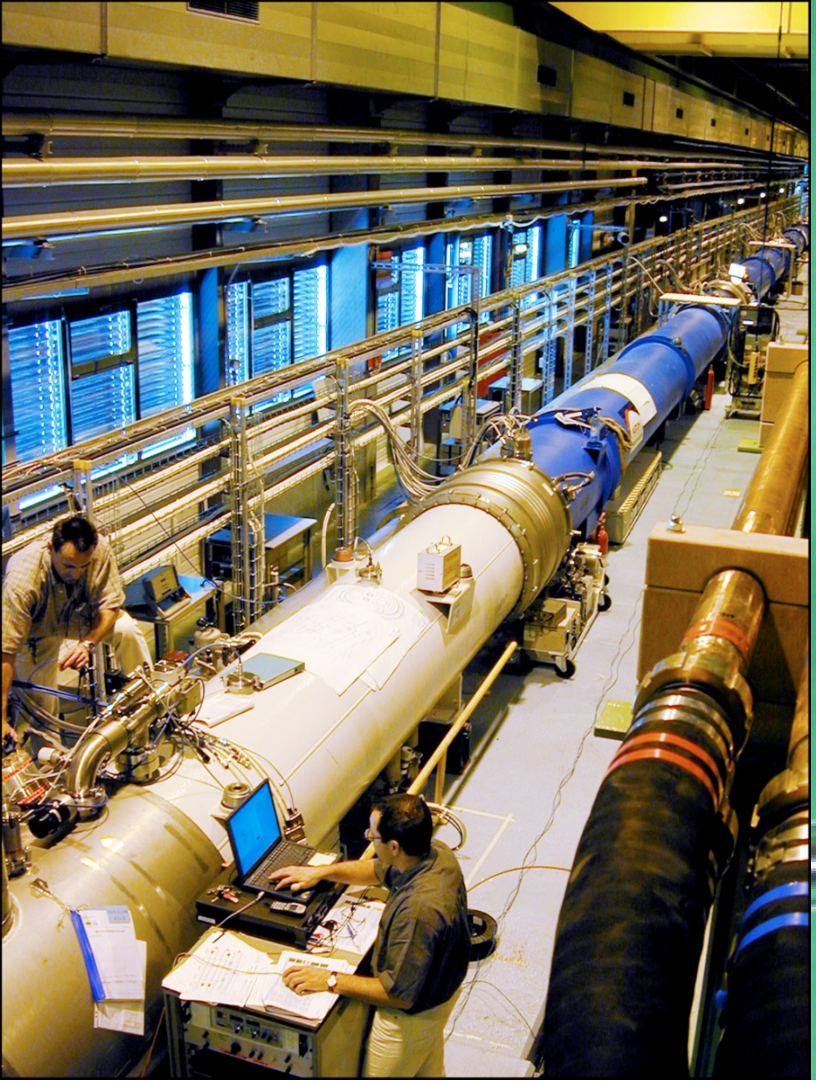
Fig. 4. Schematic illustration of spin precession in: (a) magnetic field; (b) bent crystal.

For GeV electrons, spin-flip time is 0.1 ps instead of hours (!)

$$\tau_{sf} = \frac{8\hbar}{5\sqrt{3}\alpha mc^2}\left(\frac{B_0}{B}\right)^3\frac{1}{\gamma^2} = \frac{8\hbar}{5\sqrt{3}\alpha mc^2}\frac{\gamma}{\chi^3} \qquad B_0 = 4.41\times 10^9\ \mathrm{T} \qquad \chi = \gamma\mathcal{E}/\mathcal{E}_0.$$

K. Kirsebom *et al.,* Phys. Rev. Lett. **87**, 054801 (2001)

For a Lorentz factor of 7000, spin-flip time corresponds to 49 m of bent Ge (planar channeling, perhaps axial effect could be used?)



Extraction (collimation) device – complete with power supply etc.