Potential thermal and radiation damage to crystals

in the LHC beams

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INTRODUCTION

Potential damage in long-term runs in the LHC beams:

☐ thermal

☐ radiation

Can become catastrophic under certain conditions. Monitoring was suggested by Carrigan, Jr. in 2006 (Fermilab-Conf-06-310-AD).

Limitations for safe crystal-assisted beam collimation must be established

Should not be considered as a routine technical problem.

Inherent calculation problem is due to the threshold behavior of the damage (effects can not be observed until threshold is reached):

Characteristic numbers for silicon

(a) Thermal: Brittle-to-ductile transition: T = 850 K, Melting point: 1710 K

(b) Radiation: E_d = 25 eV, 1 dpa

Simulation tools developed for CERN beams:

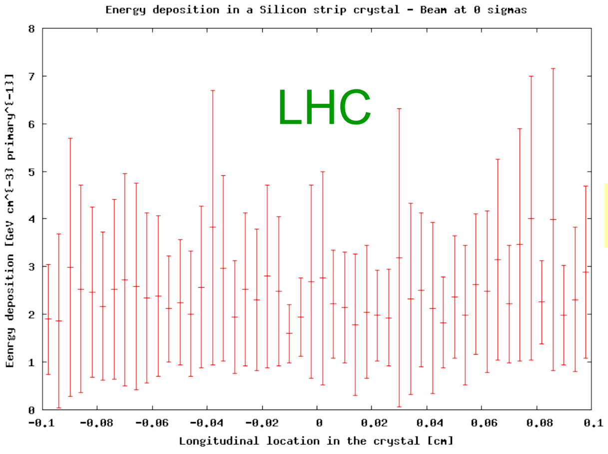
1. A. Ferrari, P.R. Sala, A. Fasso, and J. Ranft, CERN 2005-10 (2005); INFN/TC0511; SLAC-R-773.
2. A. Fasso, A. Ferrari, G. Smirnov, F. Sommerer, V. Vlachoudis, Progr. Nucl. Sci. and Techn., 2 (2011) 769—775.

Energy deposition in the crystal

Simulation is performed for the
LHC strip crystal and
SPS (NA48) crystal
(amorphous orientation)

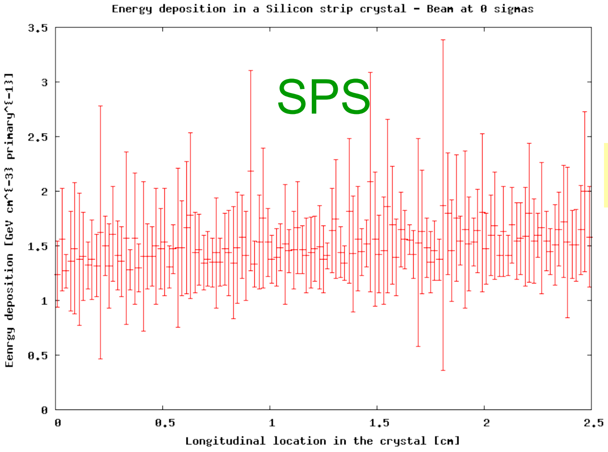
	Crystal size (mm3)	Beam size (mm)	Proton flux
LHC **7 TeV**	1 x 50 x 2	σ_X = 0.154 σ_Y = 0.412	$3.63 \cdot 10^{18}$ (prot/s)
SPS **450 GeV**	1 x 10 x 50	$FWHM_X$ = 0.8 $FWHM_Y$ = 0.3	$2.4 \cdot 10^{20}$ (prot/cm2)

Scoring energy deposition per primary proton
in the bins 20x20x40 mkm3



2.5 GeV/cm3

Z (cm)



1.5 GeV/cm3

Z (cm)

Power deposition in the LHC crystal

Consider single pass in the LHC

- Number of particles passing through the crystal location per unit time :

$$N_{norm} = f_{rev} \cdot N_{bunches} \cdot n_{part/bunch} = 3.6314 \cdot 10^{18} \text{ prot./s}$$

- Fraction of particles passing through the crystal (assuming a perfectly gaussian beam in ***x***)

	Beam part in the crystal (%)	Prot. / s	Power deposited (W / cm³)
Full impact*	99.86	$3.626 \cdot 10^{18}$	$2.03 \cdot 10^{9}$
2 σ	2.27	$8.243 \cdot 10^{16}$	$9.23 \cdot 10^{7}$
4 σ	$3.17 \cdot 10^{-3}$	$1.151 \cdot 10^{14}$	$2.03 \cdot 10^{5}$
6 σ	$9.86 \cdot 10^{-8}$	$3.581 \cdot 10^{9}$	8.02

*) at full impact, 63.3 % of the beam is lost within 0.018 seconds : the power deposited is obviously not constant

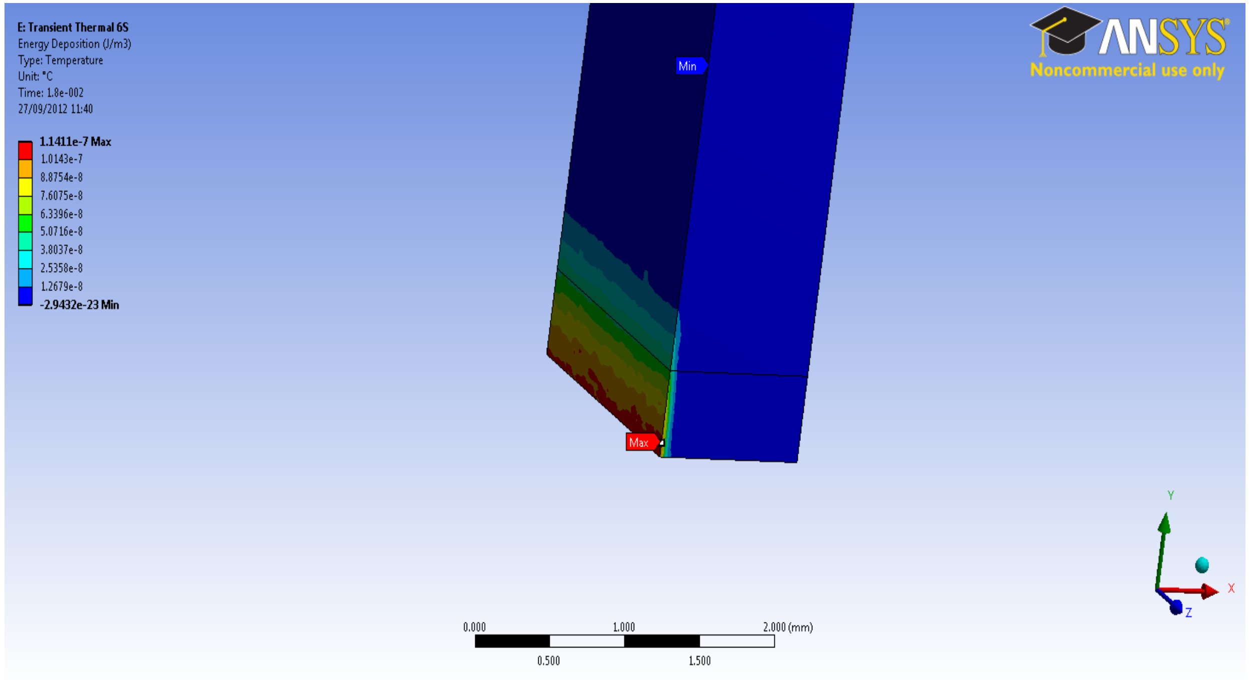
Thermal damage

Calculations of the heating of the LHC crystal exposed to full proton beam and its fractions at the levels 2σ, 4σ and 6σ are performed by using ANSYS Workbench. Heat radiation into vacuum neglected.

Problems encountered: statistical fluctuations in the input from energy deposition simulation in the FLUKA framework. Will be solved soon.

	Power deposited (W / cm³)	**Crystal temperature (K)**
Full impact	$2.03 \cdot 10^9$	$> 10^5$
2 σ	$9.23 \cdot 10^7$	> 3000
4 σ	$2.03 \cdot 10^5$	2660
6 σ	8.02	301

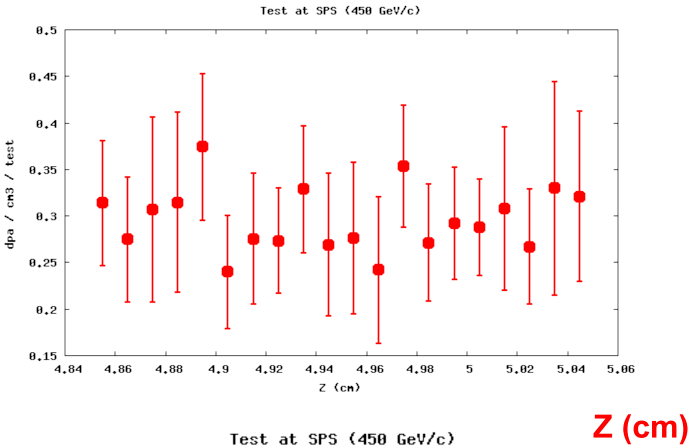
ANSYS results for 6σ option

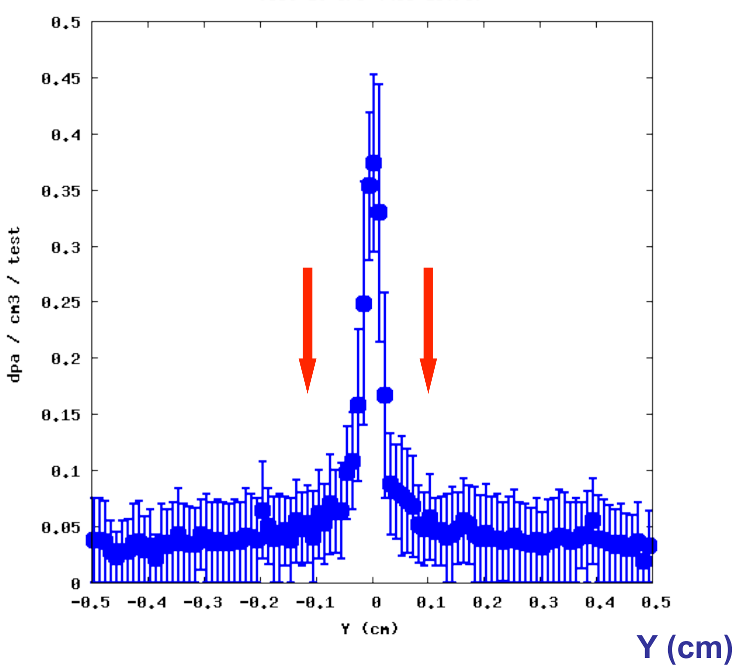


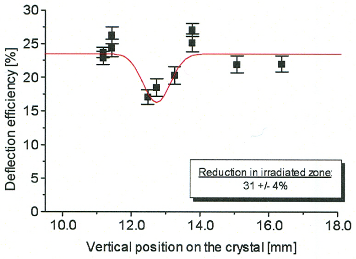
Less than 1° C increase

Simulation benchmarking with NA48 crystal

- **Si crystal -- 1x10x50 mm^3** was successfully used as bent crystal to deflect **450 GeV/c** protons from CERN SPS in 1991 to produce parallel **K_0^L** and **K_0^S** beams. In 1992 the crystal was tested by irradiating in the T6 target station of the SPS by protons during a full year.
- FLUKA simulated this experiment by using scoring binnings 20x200x100 mkm3 demonstrating that maximum damage corresponded to **0.4 dpa/cm3/test.**
- Corresponding reduction in deflection efficiency in the irradiated zone reported in A.Baurichter et al., NIM B 164—165 (2000) 27 was **31 +/- 4 %.**
- Assuming linear dependence of the reduction one obtains a deterioration coefficient **77.5 % / dpa /cm3.**





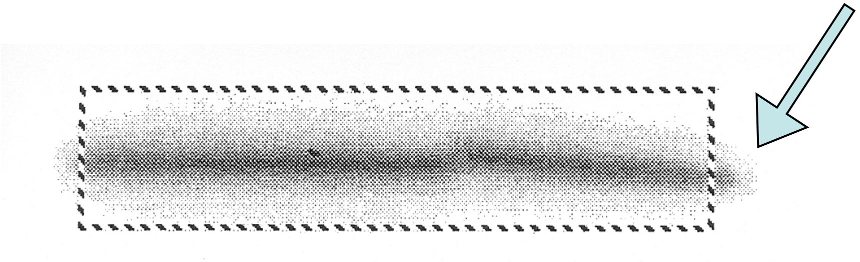


Benchmarking radiation damage effect

X-ray picture of NA48 crystal taken TWO years after exposure in the SPS beam (crystal has been broken)

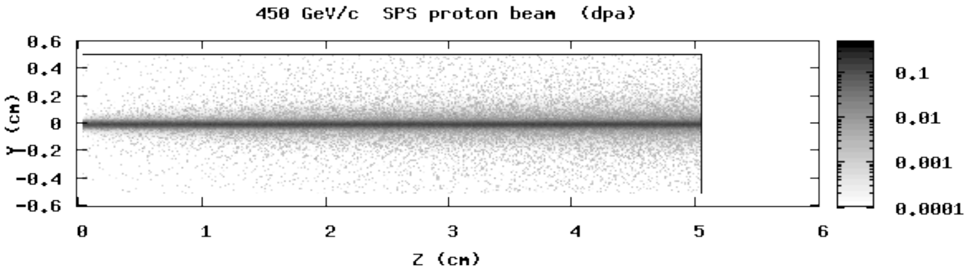
Beam area: 0.24 mm^2

Flux: 2.4 •10^{20} p/cm^2



Effect of radiography smearing

FLUKA simulation of the NA48 crystal in the SPS beam by scoring in the bins 50x50x100 mkm^3

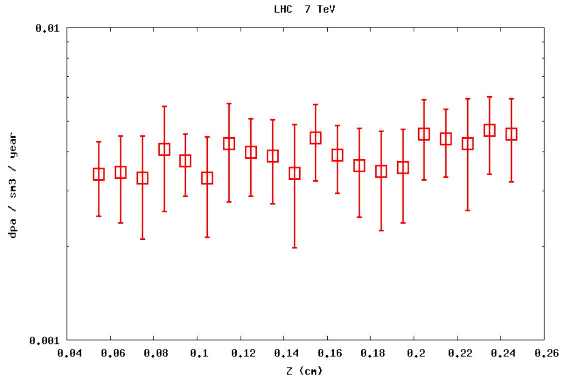


Simulation for LHC crystal (dpa)

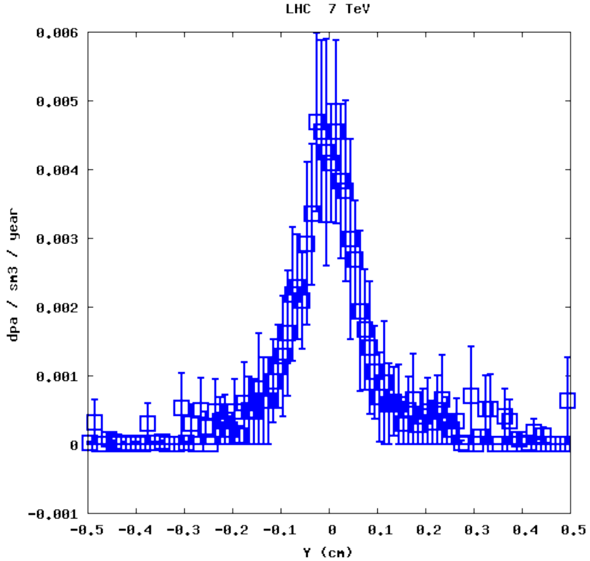
E_p = 7 TeV

Assume total beam loss due to crystal collimation as $1 \cdot 10^{16}$ prot / year. Maximum damage is then **0.005** dpa/cm3.

This can result in deterioration of deflection efficiency **0.4 % / year**.



Z (cm)



Y (cm)

Damage in the channeling orientation

New tools have been developed for FLUKA which allows one to simulate a beam passage through the crystal — see Poster PS1-09

Reduction in radiation damage is expected due to

- ☐ “Recoilless” interaction of primary particles with the crystal lattice
  → decrease in the number of PKA
  (depends on the crystal temperature)
- ☐ Channeling of a fraction of secondary particles (PKA)
  (depends on channeling probability)

Effect of the thermal motion of atoms in a crystal on the number of PKA

Consider recoil energy in an ideal crystal, *no* thermal motion:

$E_r = q^2 / 2M_{cr} \rightarrow 0$

In an actual crystal (with thermal motion) *some* fraction ***f*** **•*N*** of atoms does not recoil — no PKA produced.

Following **G. Diambrini Palazzi** (Rev. Mod. Phys. 40 (1968) 611), we find

$$f = \exp(-A q^2),$$

Where ***A*** is the mean-square thermal displacement of the atoms.

$$A = \frac{3m^2c^2}{4MK\Theta}\left[1 + 4\frac{T}{\Theta}\Gamma\left(\frac{\Theta}{T}\right)\right]$$

$$\Gamma\left(\frac{\Theta}{T}\right) = \frac{T}{\Theta}\int_0^{\Theta/T}\frac{t}{\exp(t)-1}\,dt$$

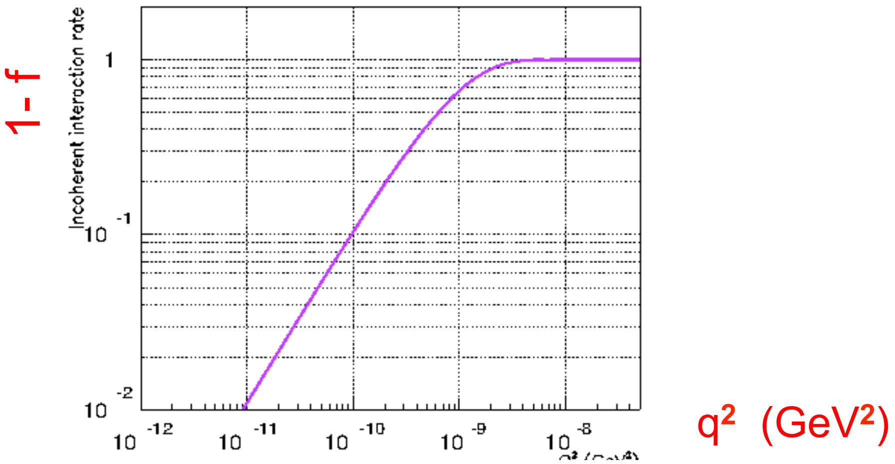
M is the mass of the silicon atom,

K is the Boltzmann constant,

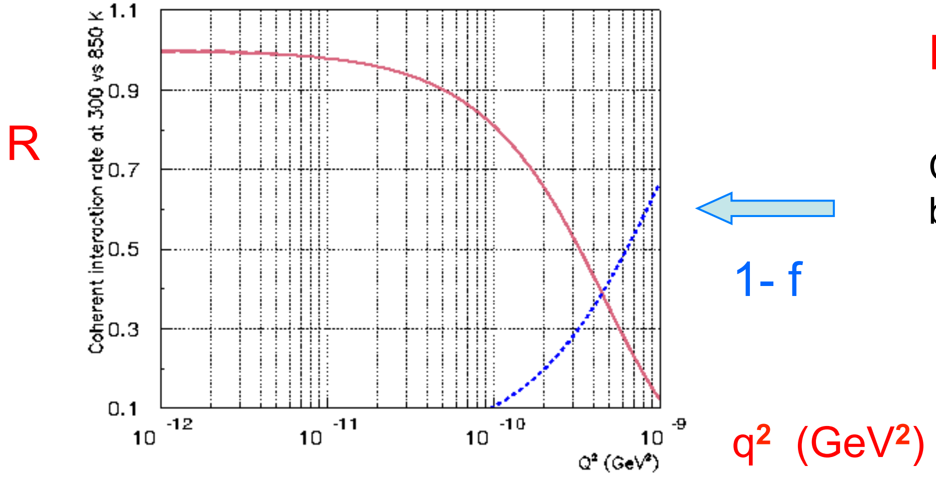
Θ is the Debye temperature of the crystal at the absolute temperature ***T***,

Γ is the Debye function

Reduction in the number of PKA



Reduction in number of incoherent recoils (PKA) as $q^2 \rightarrow 0$ at room temperature

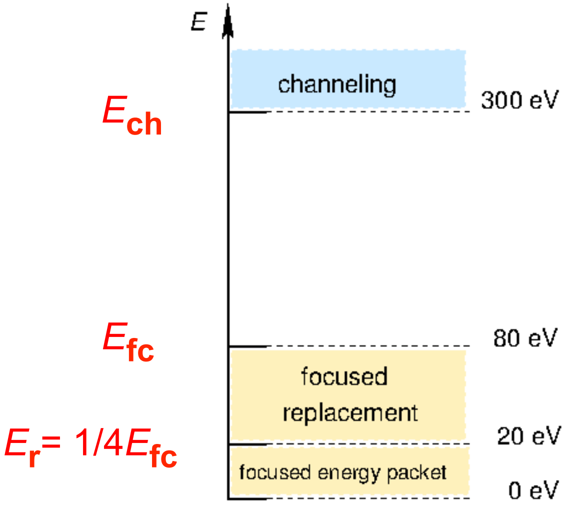


R = f(T=850) / f(T=300)

Coherent interaction rate R decreases both with temperature T and q^2

Effect of the crystal lattice on the number of displacements

- Effects of crystallinity — G.S. Was, “Fundamentals of Radiation Material Science”
- The number of displacements ν produced by a PKA can be decreased due to important effects: *focusing* and *channeling*.



Critical angle beyond which channeling cannot occur:

$$\Theta_{ch} = R_{ch} (k/E)^{1/2}$$

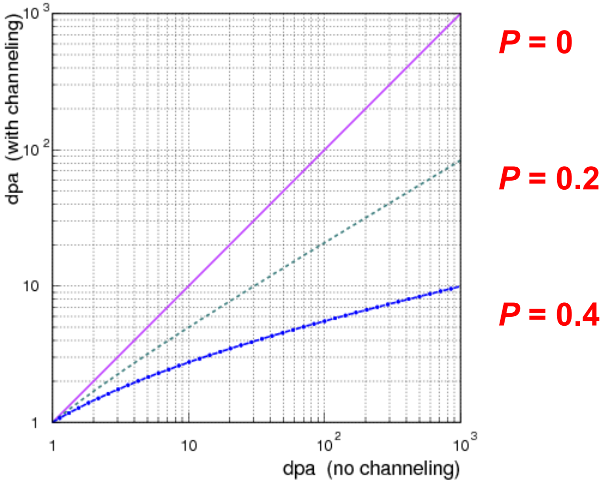
where E is the kinetic energy of the recoil atom

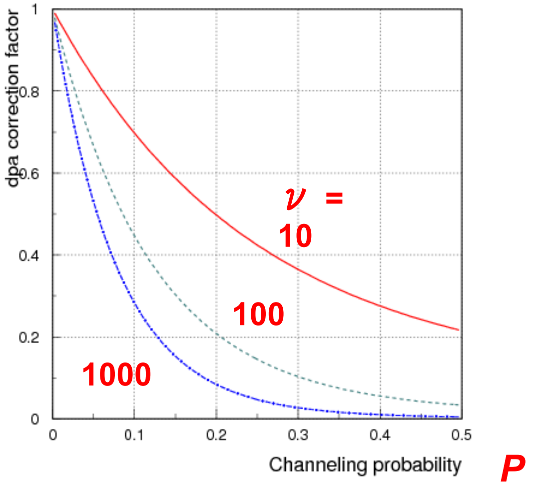
$$\nu_1^{\mathrm{cr}} + \nu_2^{\mathrm{cr}} = \frac{1}{1-2P}\left[(1-P)\left(\nu^{\mathrm{am}}\right)^{1-2P} - P\right]$$

P is channeling probability

Correction factor

$$c = \nu^{cr} / \nu^{am}$$





SUMMARY

- Limitations on application of silicon crystals for collimation of the LHC beams due to crystal damage are considered in the framework of FLUKA Monte Carlo tool.
- Possibilities of extrapolating the radiation damage considered for the amorphous crystal orientation down to channeling mode are demonstrated.
- Results of simulations obtained for the LHC beams are consistent with the damage studies for the NA48 silicon crystal in the 450 GeV/c SPS proton beam.
- It is thermal damage (melting) rather than radiation damage which can be a limiting factor for high intensities in the crystal assisted collimation at LHC.