





"Beam steering performance of bent silicon crystal irradiated with high-intensity and high-energy protons"

International HiRadMat Workshop CERN, Switzerland, 10 July 2019

Marco Garattini CERN / Imperial College London UA9 Collaboration



10/07/2019





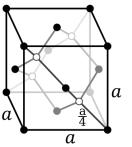


- Crystal beam steering
- Crystal applications
- Reasons to irradiate crystals
- Crystal HRMT test
- Crystal hi-dose irradiation with neutron
- Lol: HRMT test on hi-dose irradiated crystals
- Conclusions



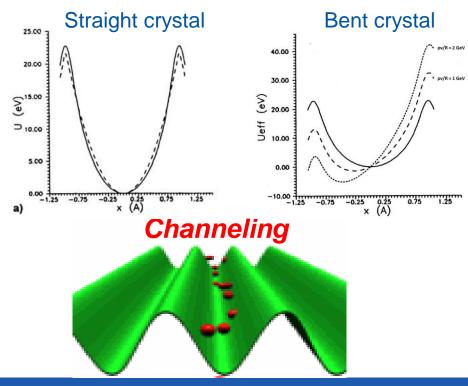


Crystal physics



Silicon diamond lattice

Potential well between two planes:



Channeling only if the protons have $p_T < U_{max}$

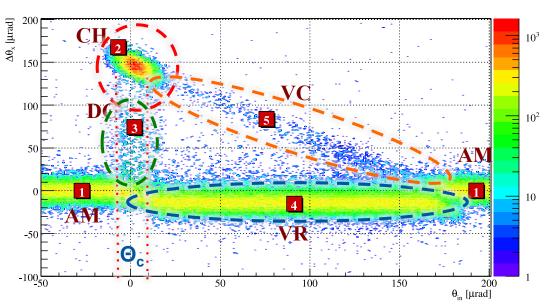
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

Typical values at energies of our interest:

Case	$\begin{array}{c} {\bf Energy} \\ [{\rm GeV}] \end{array}$	$ heta_c \ [\mu rad]$	$\lambda \ [\mu m]$
SPS coast	120	18.3	33.0
SPS coast	270	12.2	49.6
H8	400	10.0	60.3
LHC inj.	450	9.4	64.0
LHC top	6500	2.5	243.2
LHC top	7000	2.4	252.3

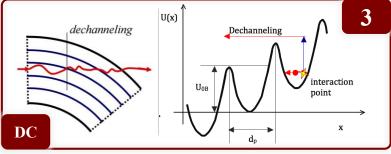


CÉRN Coherent processes in bent crystals[1] **From test beam** on the CERN-SPS extraction line H8:

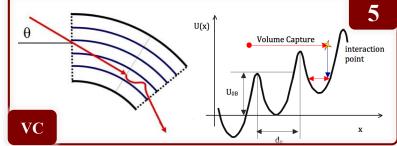


(in the framework of the UA9 experiment)

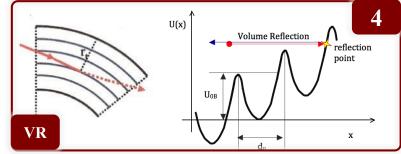
Dechanneling

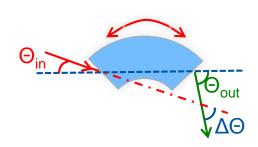


Volume capture

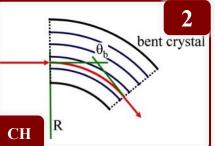


Volume reflection











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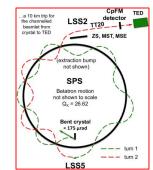


Crystal applications

- LHC Crystal Collimation for Hi-Lumi [2]: use of a bent crystal to deflect beam halo particles instead of 3 stages of standard collimators (successfully proved in the LHC)
 - Reduced off-momentum losses in DS
 - Impedance reduction
 - Simpler and cheaper solution



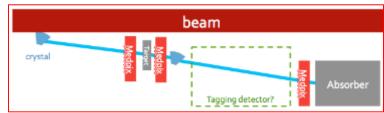
- SPS extraction [3,4]: use of a crystal to extract (or support the extraction) from the SPS to the North area (successfully proved in the SPS)
 - Reduction of losses at the extraction septum
 - Simpler and cheaper solution



- Beam splitting for LHC: use of two crystal in a raw to split the halo beam and send it

on a fixed target (preliminary proved in SPS)

 At now the only way to split the LHC beam inside the LHC itself





Reasons to irradiate crystals

No systematic study of irradiated crystals has ever been carried out until now

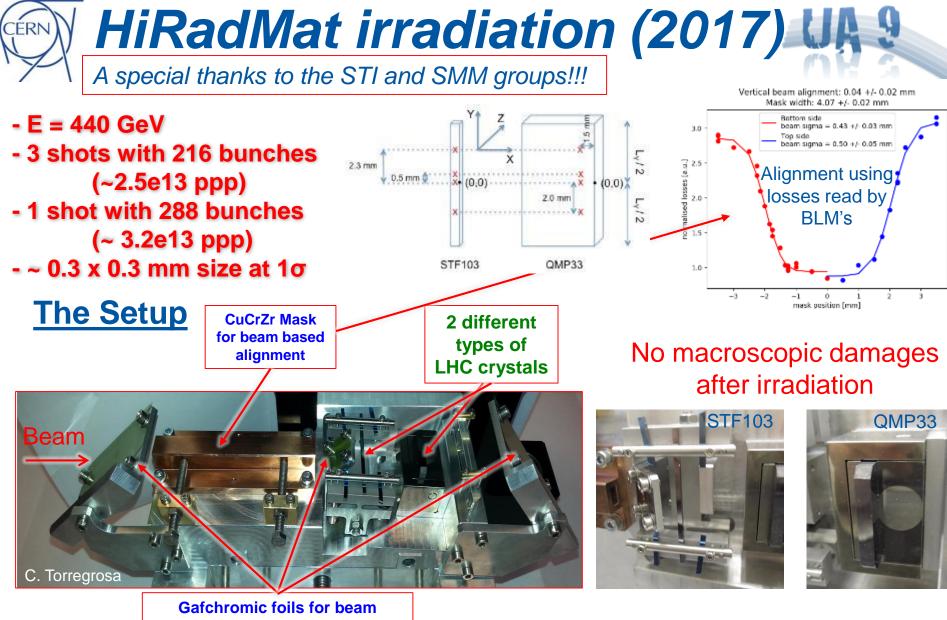
- High-intensity and energy particles could produce thermo mechanical stresses on the crystal system: deformations, evaporations, vetrification, craks, etc...
- HiRadMat test at CERN to study consequences of unwanted fast irradiations during injection or dump procedures

- High fluxes particles produce crystal lattice damages that affects the channeling performance (the channeling efficiency)



- Efficiency test before and after irradiation to test their robustness





impact crosscheck



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HiRadMat Crystals H8 results

2 LHC crystals irradiated in HiRadMat and tested before and after in H8

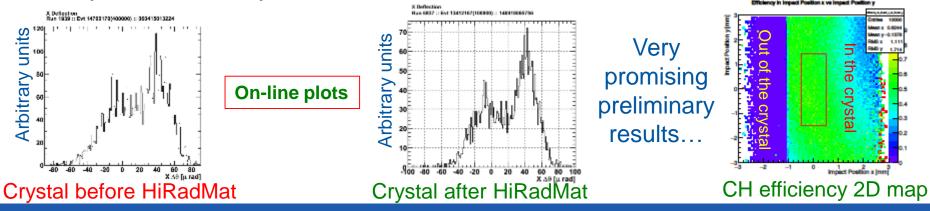
1st crystal fully analysed: tested with different beams: 400 GeV p & 180 GeV h⁺

Crystal	Θ _{CH} (before)	Eff. (before)	Θ (after)	Eff. (after)
	(±1 µrad)	(±2 %)	(±1 µrad)	(±2 %)
STF103	55 (400 GeV <i>p</i> +)	75 (400 GeV <i>p</i> +)	54 (180 GeV π+)	69 (180 GeV π+)

Crystal of the same kind of the STF103, tested with different beams but not irradiated

Crystal	Θ _{CH} (400 GeV <i>p</i> ⁺)	Eff. (400 GeV <i>p</i> ⁺)	Θ _{CH} (180 GeV <i>h</i> *)	Eff. (180 GeV <i>h</i> ⁺)
	(±1 μrad)	(±2 %)	(±1 μrad)	(±2 %)
STF105	51	74	52	64

- 2nd crystal under analysis: tested both times with 180 GeV h⁺





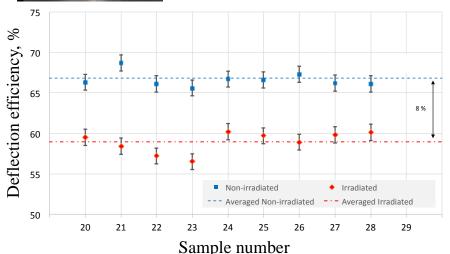
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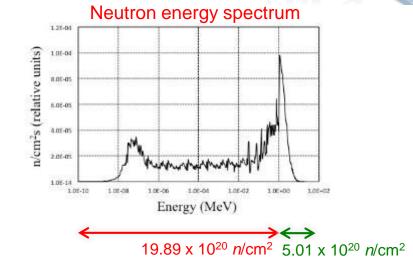
Crystal hi-dose neutron irradiation

- A special thanks to the STI group !!!
- 9 crystal samples have been irradiated at the SCK-CEN BR2 reactor
- with 2.5 x 10²¹ neutrons/cm²
- 0 < E < 10 MeV



Two crystals samples ready to be measured in H8





- All the 9 crystal samples has been tested in H8 before and after the irradiation in the same conditions

- In particular, their channeling efficiency has been measured
- A mean channeling efficiency reduction of
- ~ 8 % after the irradiation has been registered



Crystal operational lifetime estimations

- To estimate the real crystal robustness in a hi-energy and intensity particle accelerator, we have to rescale the neutron effect to the proton and heavy ions ones, at different energies

- The parameter used for this rescaling is the number of Displacements Per Atom (DPA) produced during the irradiation

- Using FLUKA it was possible to compute the DPAs produced by the neutron spectrum of the BR2 reactor, by proton and Pb ions at different energies, computing the equivalent doses that produce ~ 8% of channeling efficiency decrease

- LHC collimation:

considering the LHC operational range in 2018, the crystal will lose ~ 8 % in efficiency in a time between ~ 5 and ~27 years

- SPS extraction (shadowing):

considering the machine parameters of the successful test performed in 2018, the crystal will lose ~ 8 % in efficiency in ~ 82 years

These results are a crystal reliability proof in terms of radiation hardiness, also in hi-intensity hadron accelerator applications



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Lol: Crystal HiRadMat test on high-fluxes irradiated crystals

New HiRadMat test on high-flux irradiated crystals: to test crystal robustness to fast irradiation during injection or dump procedures at the end of their operational lifetime

The new HiRadMat test will be almost the same of 2017:

- Same beam features
- Same supports, tank, etc...
- Same alignment procedure
- only the crystals will be different: irradiated instead of not irradiated

Quite simple and standard test, but extremely important to verify the reliability of the crystal technology

2019: Letter of Interest from UA9 and STI group

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> His Saleman (Hi Sh) Ontenal of the UKS collaboration







References



The studies about neutron irradiation have produced a paper recently submitted to the *"European Physics Journal C"*

The paper about the HiRadMat test are almost ready and will be submitted soon to the "European Physics Journal C"

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[1] M. Biryukov, Y. A. Chesnokov, and V. I. Kotov, "Crystal channeling and its application at high-energy accelerators". Springer Science & Business Media, 2013

[2] W. Scandale et al., "Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC", Phys. Lett. B, 2016

[3] Fraser, M. A., *et al.* "Experimental results of crystal-assisted slow extraction at the SPS." *arXiv preprint arXiv:1707.05151* (2017).

[4] F. Addesa *et al.,* "The SE-CpFM Detector for the Crystal-Assisted Extraction at CERN-SPS", 6th Int. Beam Instrumentation Conf.(IBIC'17, Grand Rapids, MI, USA, 20-24 August 2017. JACOW, Geneva, Switzerand, 2018





Conclusions



- The HiRadMat test proves the crystal robustness also in case of a machine accident
- Crystal robustness test with hi-fluxes of neutrons is a proof of the crystal radiation hardiness also in hi-intensity hadron accelerator applications
- The same test will be performed with hi-fluxes of protons
- Future HiRadMat tests on hi-dose irradiated crystals (both with neutron & protons) are fundamental to definitely prove the reliability of the crystal technology







Thank you for your attention ! Ľ thanks a lot to all the UA9, EN and HRMT colleagues strongly involved !!!



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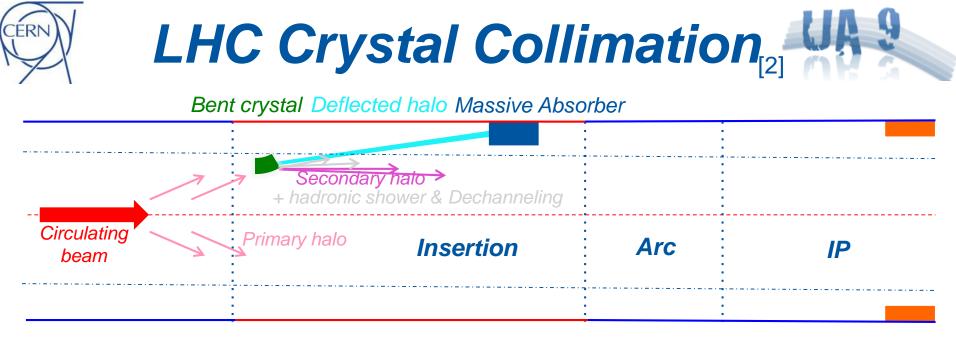


Facility	IHEP U-70	SPS North Area – NA48	HiRadMat
Reference	Biryukov et al., NIMB 234, 23-30	Biino et al., CERN-SL-96-30- EA	IPAC13 (THPFI059)
Year			2012
Beam	70 GeV protons	450 GeV protons	440 GeV protons
Irradiation	 50 ms spills of 10¹⁴ p one spill every 9.6 s several min of irradiation 	• 2.4 s spills of 5×10^{12} p • one spill every 14.4 s • one year irradiation $(2.4 \times 10^{20} \text{ p/cm}^2 \text{ in total})$	 7.8µs pulses of 3.2×10¹³ p Several shots
Findings	channelling efficiency un- changed	channelling efficiency reduced by 30%	no visual damage, change in channelling efficiency to be evaluated

Moreover...

- UA9 tested several bent silicon crystals for collimation MDs in SPS and LHC
- Crystals have been irradiated for years during MD operations
- Crystals suffered some accidental beam impacts
- Crystals have shown always the same performances (angle and efficiency)
- Crystals did not show macroscopic damages

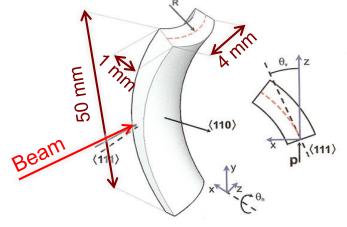




Main gains:

LHC design parameters for Silicon ST Crystals

- Reduction of inelastic nuclear interactions
 Reduced off-momentum losses in DS
- Less collimators and with larger gaps
 Impedance reduction
- Similar performance with both p and Pb
 Significant improvement of w.r.t. present



Bending 50µrad B ≈ 300 T @ 7 TeV!





SPS crystal extraction

2016 - slow non-local extraction of 270 GeV *p*⁺ in channeling mode [6] [7] beam into the TT20 extraction line towards the North Experimental Area of the SPS was demonstrated using the extraction septa and a bent crystal

Circulating beam 270 GeV p+ a 10 km trip fo the channelled heamlet from crystal to TEF ZS. MST. MSE crysta ≈175 urad at -60 TACW inserted extraction bump not shown) s relative to crystal in LSS5 [m] Extraction SPS Edge of the Betatron motion NDCH(xi)/dx in 2 turns not shown to scale circulating $Q_x = 26.62$ beam core Bent crystal = 175 µrad Nсн Halo density in septum Data – Background turn 2 Gauss + Expo (Analytical) channeling mode LSS5 TACW OUT: TACW OUT: CH: mean +/- 30 UA9 CpFM Virteano along the CH beam in TT2 DCH: xi [2.5 ; 4.0] mm eam in TT20 Septum width of dx mm ("Cherenkov for proton horizontal axis thick Flux Measurements") (self-normalized to the Extracted ACW N: beam stopped in LSS5 2 mm detector for SPS and total No of impinging LHC has seen the particles) extracted beam Figure 4: TT20 CpFM signal rate (red) vs. TACW position X (mm) (blue) [19]. loss ratio R \approx N_{DCH} / N_{CH}= \sim 6 ‰

20 TCXHW

15 retracted



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2018 - "Virtual" non-resonant local beam

QD.521

TAL

retracted

QF.518 QD.519 QF.520

TCSM

retracted

extraction of 270 GeV p^+ in channeling mode

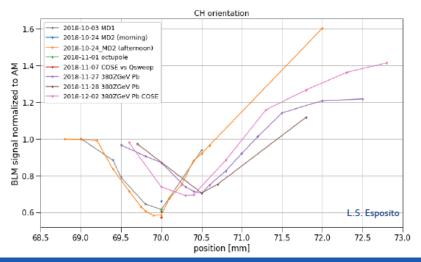
Joint activity with TE/ABT and EN/STI

Limepix



SPS slow extraction with crystal shadowing

- This technique is developed to reduce the number of particles on the SPS extraction septum (ZS wires) and consequently the extraction losses
- A crystal is used upstream to shadow the ZS wires deflecting the particles that would hit him
- In 2018, a feasibility test has been performed and a reduction of 40 % of losses with protons and 30 % with lead ions was observed



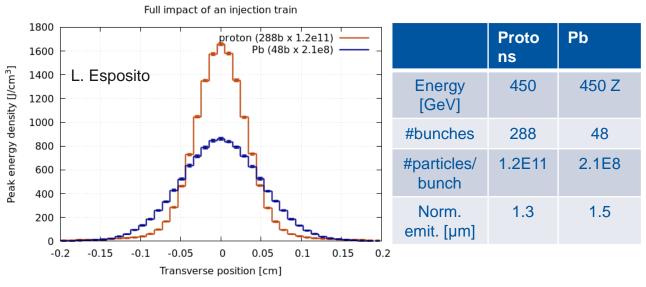




FLUKA simulations



Accidental impact on crystal at injection



- Impact of a full injection train on TCPCV.A6R7.B2 (smaller $\beta_x \cdot \beta_y$)
- Crystal assumed as amorphous
- Same optics for the injection of proton and Pb

Remark on induced energy densities:

- Due to small dimensions of the crystal (4 mm thick) peak energy density dominated by ionising energy loss of impacting protons
- Electronic stopping power of protons in silicon only varies by 10% between 440 GeV and 7 TeV → a test in HiRadMat with 288 bunches at 440 GeV allows also for conclusion valid at higher energies
- For an asynchronous beam dump at top energy few bunches are expected to be lost on the crystal



UA9 Experimental apparatus at the H8 SPS extraction line

High rate and high angular resolution beam telescope based on CMS Tracker HW&SW

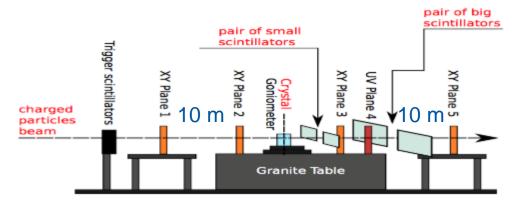


FIG. 1: Experimental layout in the H8 beam line.

Main steps in the characterization of bent crystals:

- 1. Alignment run: only the tracking stations are in the beam line
- 2. Linear scan: the crystal is placed on the beam line
- 3. Angular scan: ~10⁵ events/step are acquired around the channeling orientation looking for CH
- 4. High statistics runs:
 - the crystal is left in the optimal channeling position for hi-stat. of ~16 M events



FR

International HiRadMat Workshop, CERN



M. Pesaresi, T. James, J. Borg



Systematic error < 1µradStatistical error negligible



Rescaling to different particle and energy



- To estimate the real crystal robustness in a hi-energy and intensity particle accelerator, we have to rescale the neutron effect to the proton and heavy ions ones, at different energies

- The parameter used for this rescaling is the number of Displacements Per Atom (DPA) produced during the irradiation

$$DPA = \frac{1}{\rho} \Sigma_i N_i N_i^F$$

 ρ = atomic density

Ni = number of particles per interaction channel

 N_i^F = number of Frenkel pairs (dislocations)

- Using FLUKA it was possible to compute the DPAs produced by the neutron spectrum of the BR2 reactor and by proton and Pb ions at different energies

Part.	E [GeV]	DPA [p.p.p.]	$\phi_{eq} \ [1/cm^2]$
n	Spectrum	$5.7\cdot10^{-20}$	$2.5 \cdot 10^{21}$
р	400	$5.8\cdot10^{-20}$	$2.4\cdot10^{21}$
р	$6.5\cdot 10^3$	$6.2\cdot10^{-20}$	$2.3\cdot10^{21}$
\mathbf{Pb}	$400 \cdot Z$	$4.7\cdot 10^{-17}$	$3.0\cdot10^{18}$
\mathbf{Pb}	$6.5\cdot 10^3\cdot Z$	$4.8\cdot 10^{-17}$	$2.9\cdot 10^{18}$

