Crystal installation at SPS: Operational scenarios and failures cases

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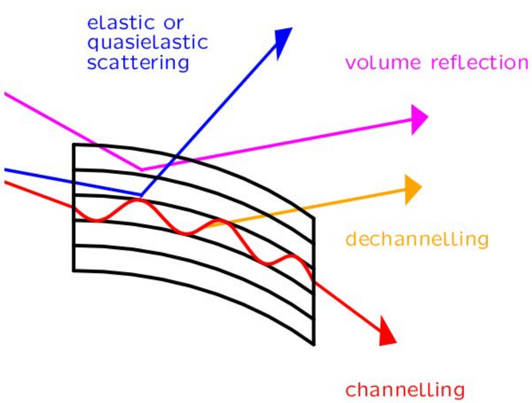
Introduction to ZS crystal shadowing

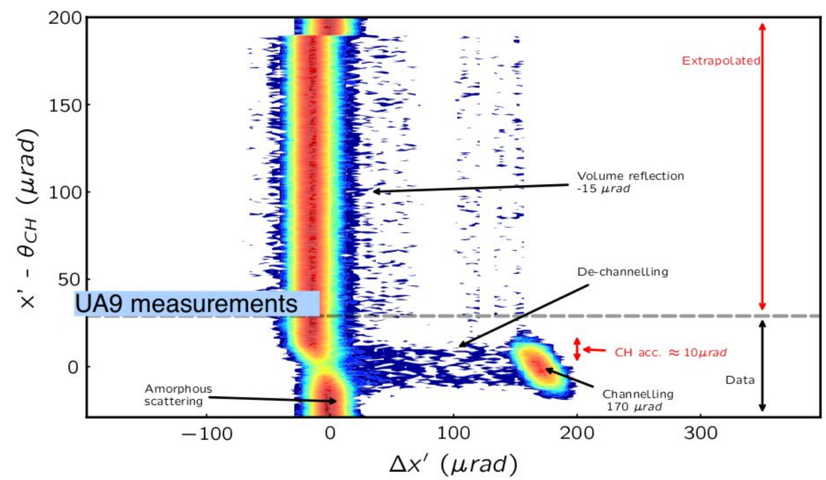
Introduction

- Slow extraction, based on third-integer resonance, comes with unavoidable losses at the electrostatic septum (ZS)
- R&D carried out over the last 5 years to arrive at a crystal shadowing system ready for operational deployment
- Continuous flow of particles from beam core to large amplitudes following (almost) straight separatrix
- ZS thin wires are responsible for separating the extracted from circulating one) direct exposure of wires to primary particles!
  - About 3% of the circulating beam lost in the slow extraction channel
- This is the main limiting factor to the deliverable protons on target (POT) from the SPS
- Prototype crystal (TECS) was installed in LSS2 for MDs and tests of the shadowing concept (ECR: EDMS#1997264):
- Scope of today's MPP presentation is preparation for:
  - Operational deployment of the LSS2 TECS in 2021
  - ECR for installation of LSS4 TECS in YETS2021/22

Introduction

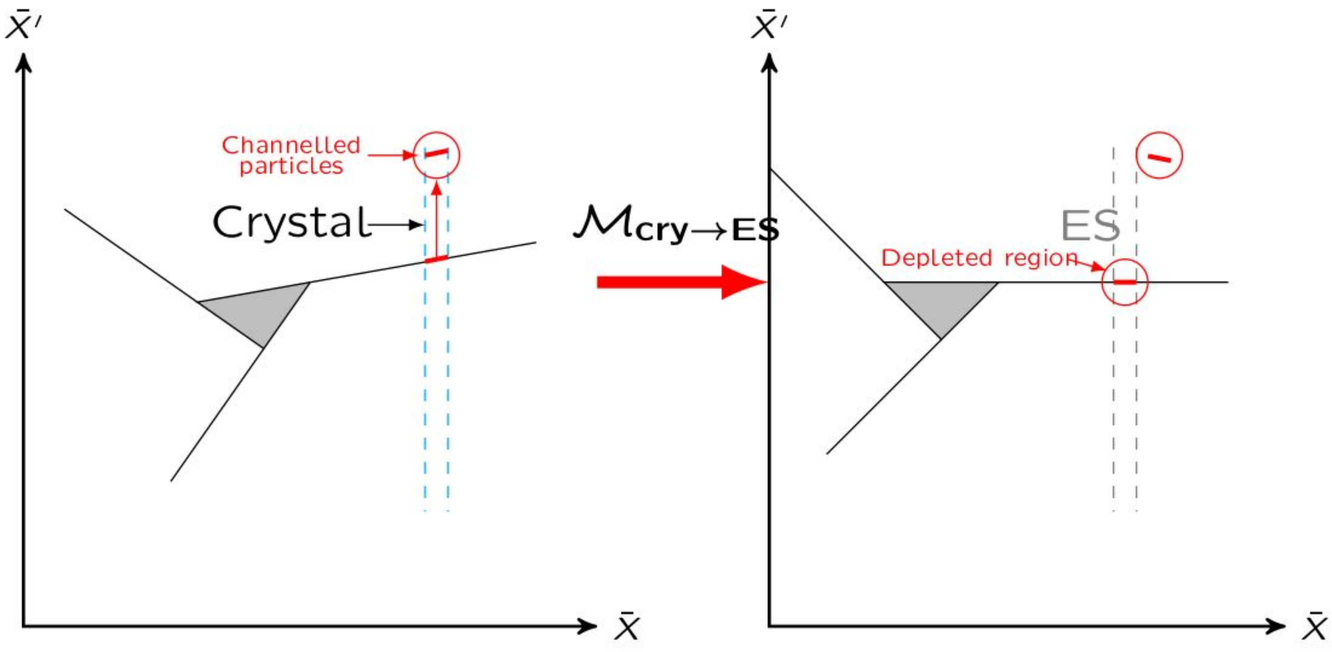
➔ Si bent crystals can be used as loss reduction devices for slow extraction
➔ For example, a single 2 mm long crystal can deflect 400 GeV protons by 170 microrad: this corresponds to ~120 T magnetic field!
  - They can be made very thin
  - They can deal with large intensities
  - Very low probability to produce losses due to their low probability to perform inelastic interactions
➔ Non-linear tracking simulations carried out including an empirical 2D Probability Density Function (obtained from UA9 measurements) representing the crystal as a thin kick (no inelastic interactions considered)





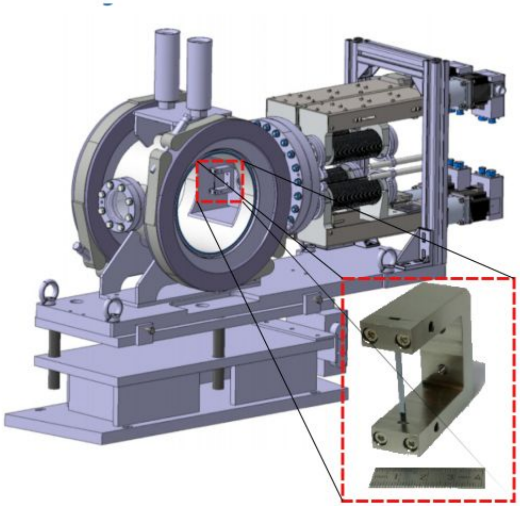
Introduction => Shadowing

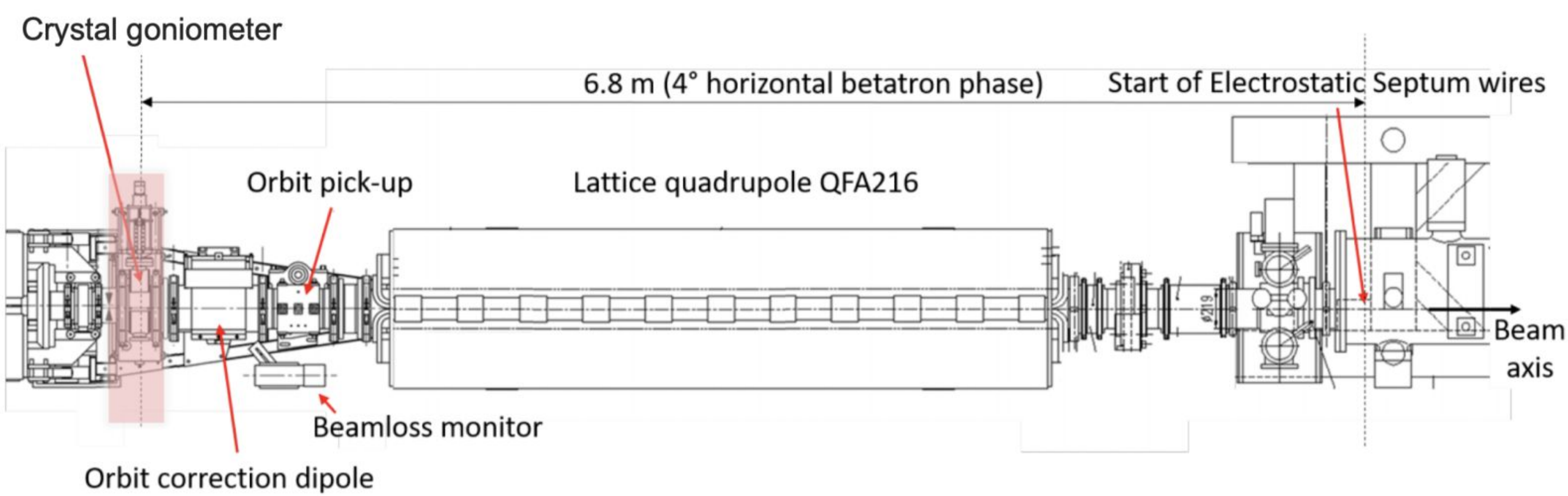
- ➔ A thin bent crystal is placed to n x π + $\Delta\mu_x$ from the ES (n integer and $\Delta\mu$ sufficiently large to fit ES wires)
- ➔ The crystal, interacting with the beam, reduces the particle density on the extracted separatrix in very well defined transverse region
- ➔ The depleted region is then aligned with the ES



TECS in LSS2 SPS: system as installed

- ➔ A goniometer with the specified crystal characteristics was installed in the SPS
- ➔ The total tank length is only 187 mm!
- ➔ The very short device was developed with UA9 and installed 7 m upstream the beginning of the ZS
- ➔ The crystal itself is 0.8 mm thick and 2 mm long for a vertical extension of 35 mm

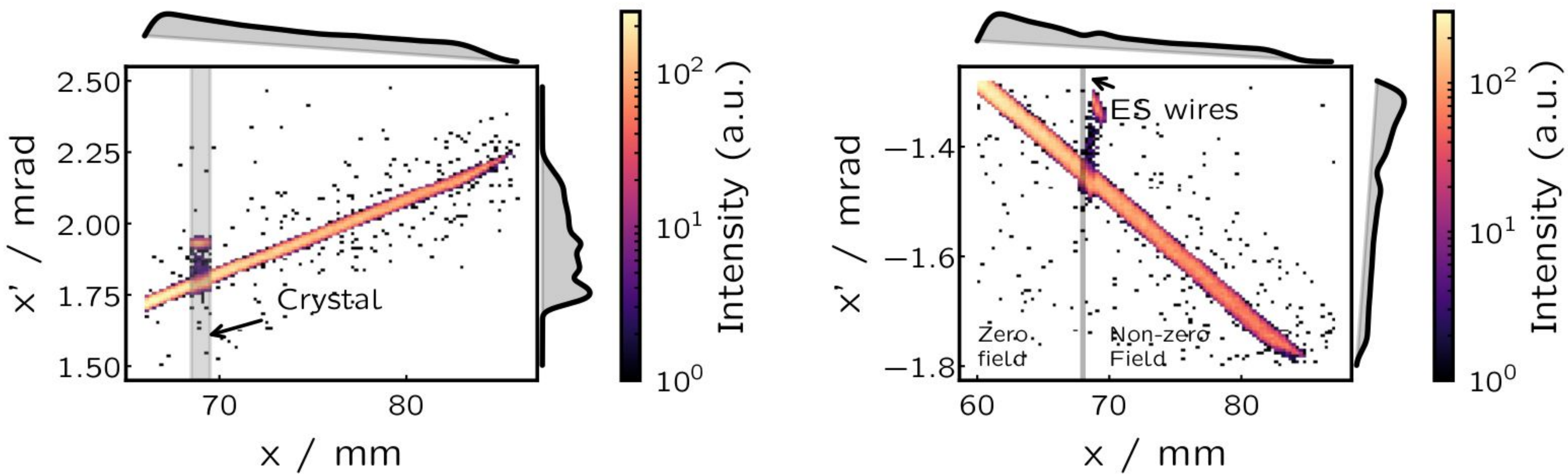




Local crystal shadowing from LSS2

- ➔ A loss reduction factor of x2 expected from simulations
- ➔ This was measured in 2018 and ~40% loss reduction was achieved (when in channelling, CH)
- ➔ ~20% achieved when in volume reflection (VR)

Tracking simulations for shadowing



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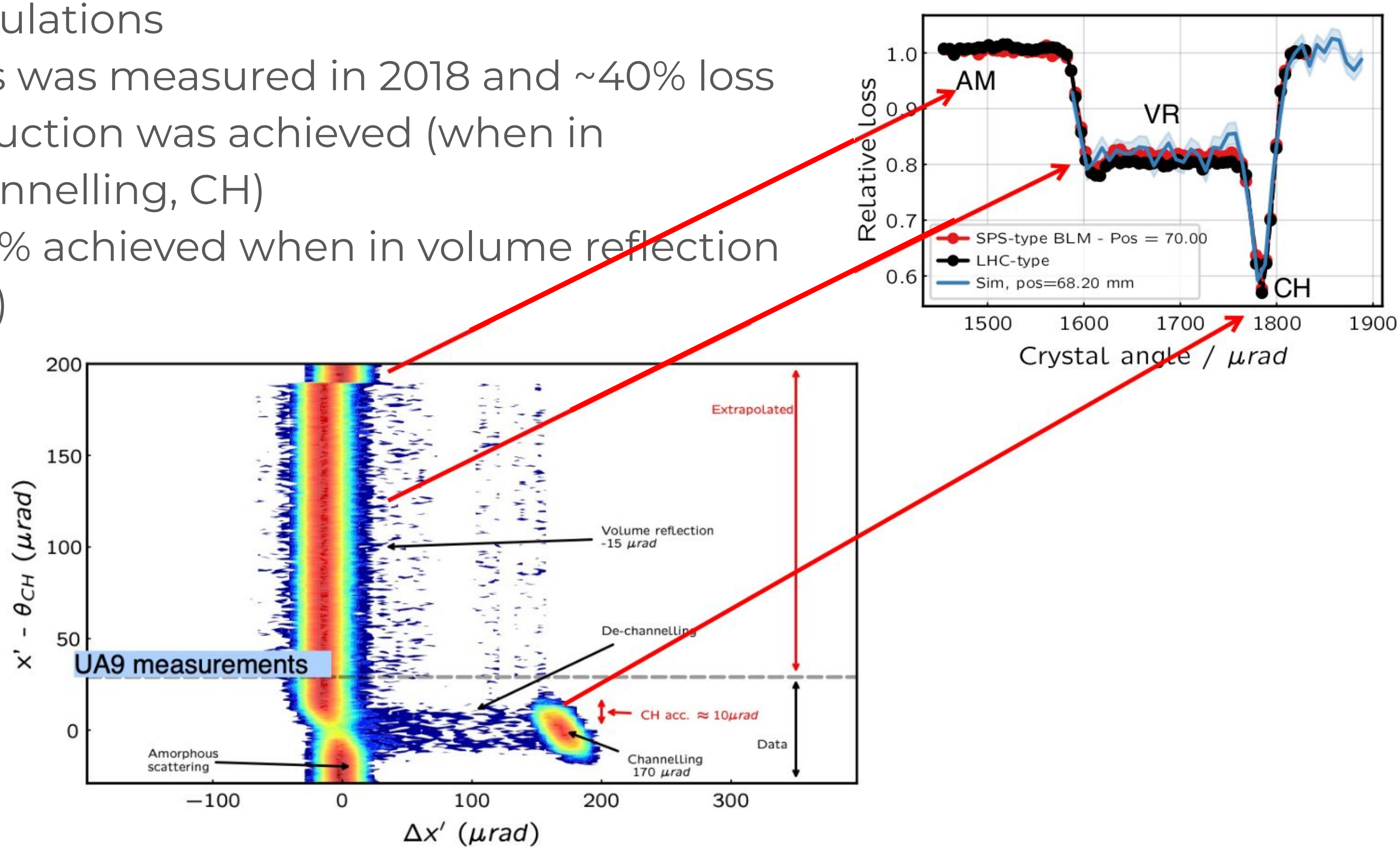

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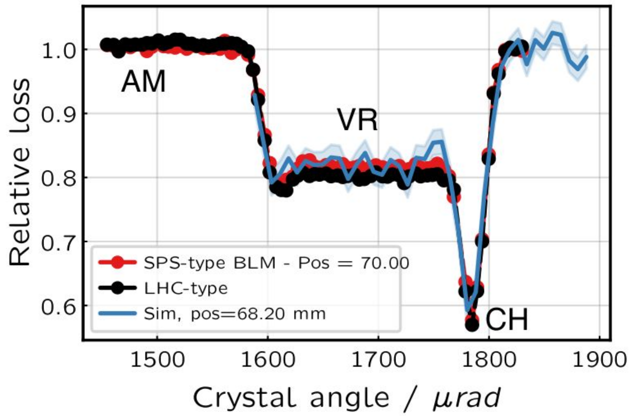
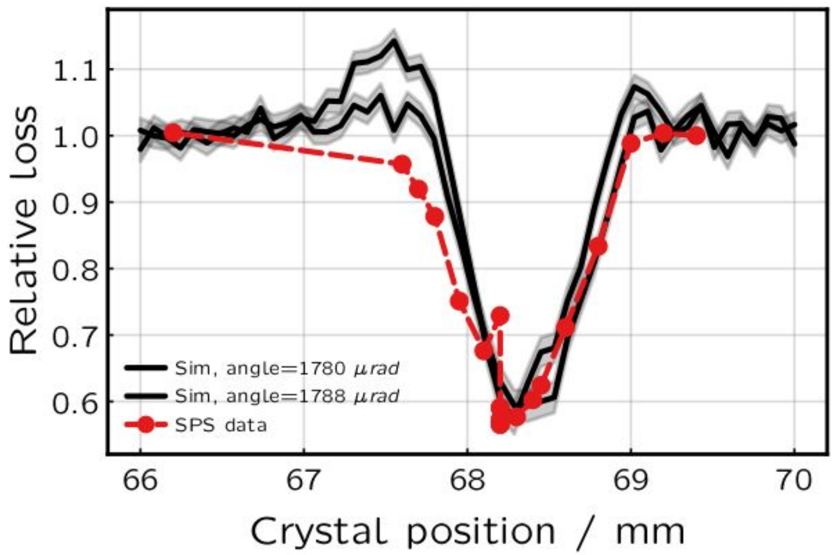
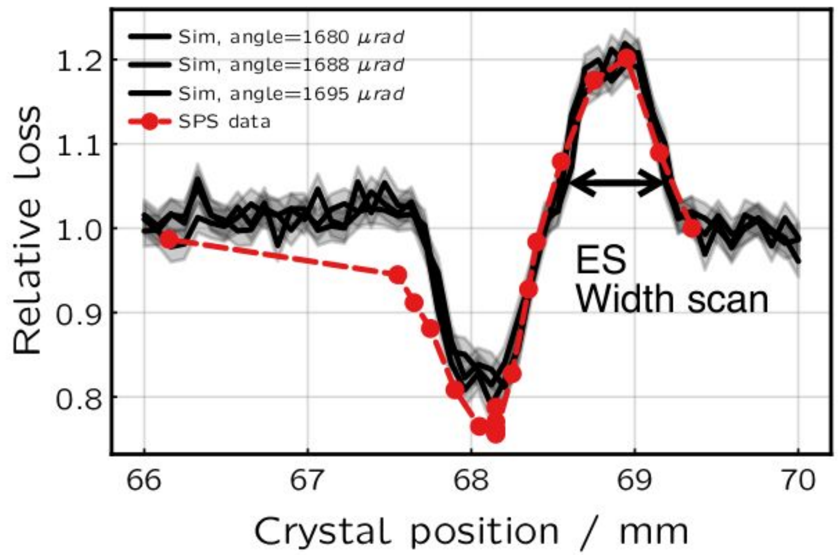


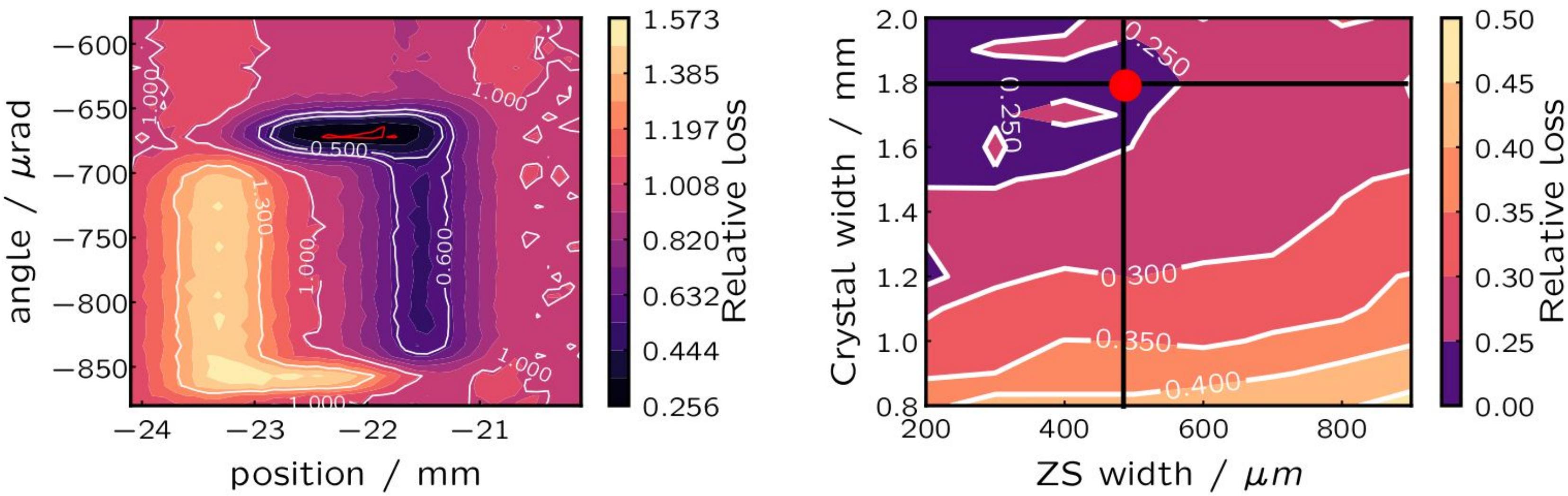




Non-local crystal shadowing from LSS4

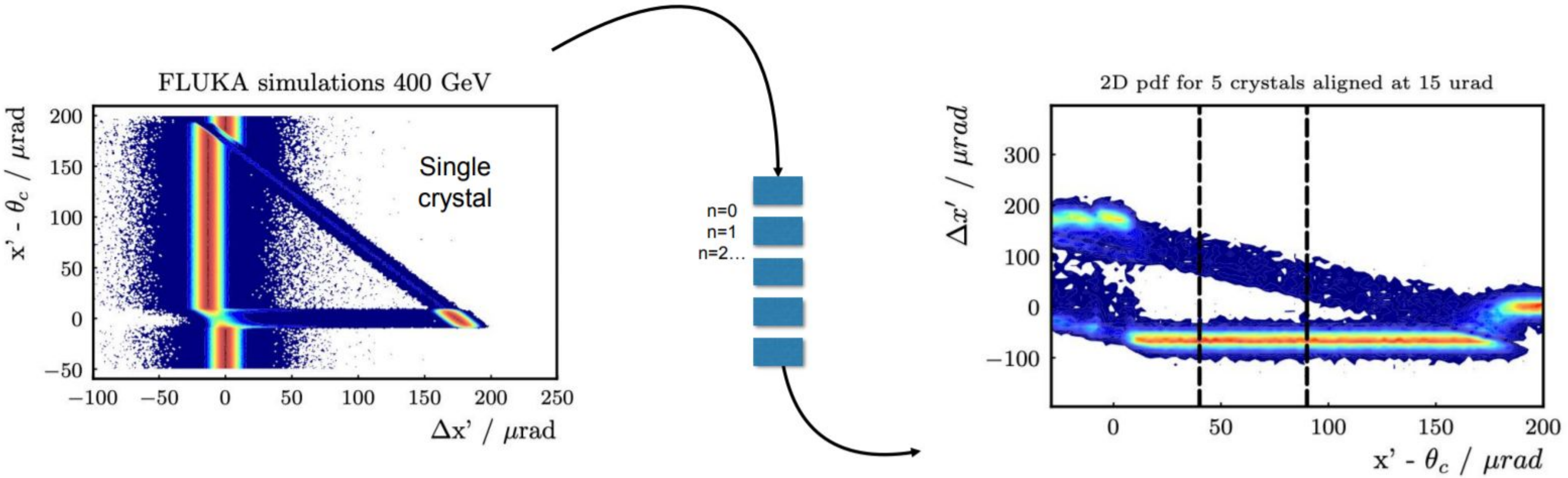
- ➔ To try to improve the loss reduction, we proposed a better suitable location => exploitation of machine non-linear elements (extraction sextupoles mainly) to enhance separatrix depletion
  => **crystal in LSS4 => x4 loss reduction with single crystal**
- ➔ ...can we do better?

Tracking simulations for shadowing



Non-local crystal shadowing from LSS4

- ➔ Exploiting efficiency of VR and adding up deflection angles with **Multi VR Arrays (MVRA)**, we can get to **x10 loss reduction at the ZS from LSS4**
- ➔ MVRA crystals will come in a second stage, hopefully installed in LSS4 at the end of 2022
- ➔ We will start with single crystal in LSS4 in 2022 (SRR EDMS#2382192)



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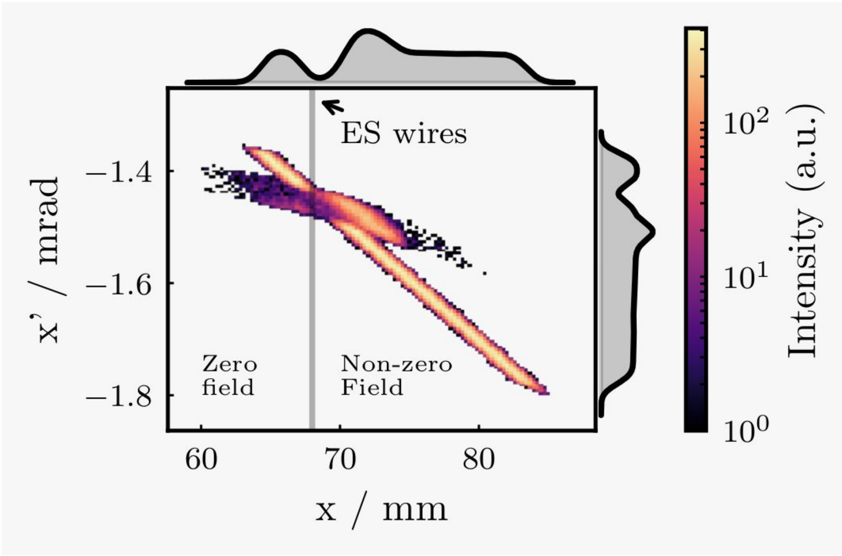
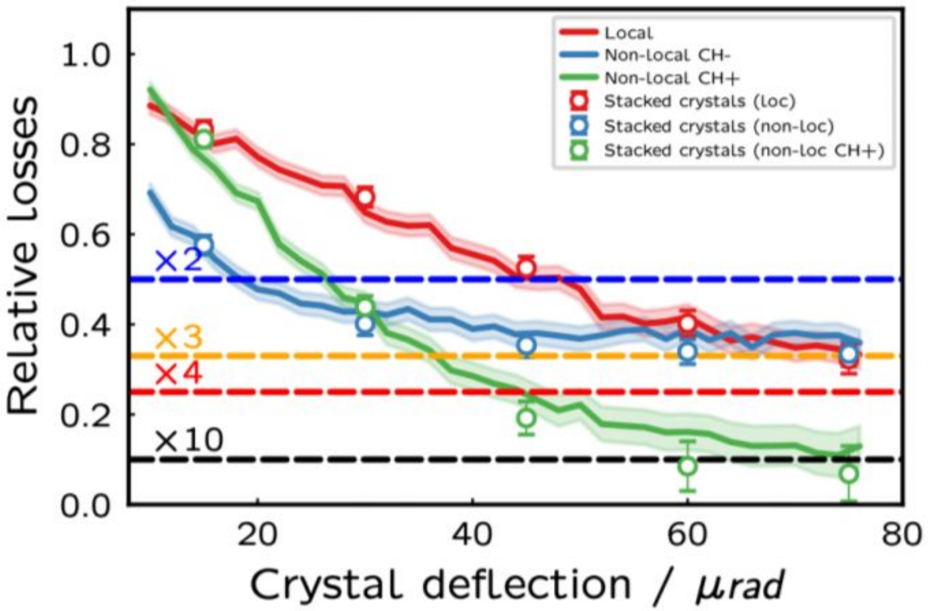




Operational scenarios and possible failures of TECS in LSS2 and LSS4

TECS in LSS2: operational scenarios

- ➔ TECS in LSS2 to be commissioned as OP device in 2021:
  - Exploit re-commissioning period to repeat 2018 “reference” measurements with new ZS system (new septa installed in LS2)
- ➔ **Expect to be OP-ready in VR immediately**
  - Operational test in VR carried out in 2018 for 13 hours with success [1] with stable loss reduction of 20%
- ➔ OP-readiness in CH depends on success of MSSB splitting efficiency (MD time requested, if needed) and stability in CH
  - See commissioning plan [2]
  - Need to slightly modify optics in TT20 (1x quad strength -20% towards the end) and 2 closed bumps as studied by P. Arrutia [3]
  - Need to test stability in CH over longer time periods
  - Important to check energy deposition on TCSC/MSSB for beams extracted with TECS: **no show-stoppers expected** (to be done by EN-STI using parameters in EDMS #2360012)
- ➔ **Interlocking extended to the OP device as described in Mario’s talk**

TECS in LSS4: operational scenarios

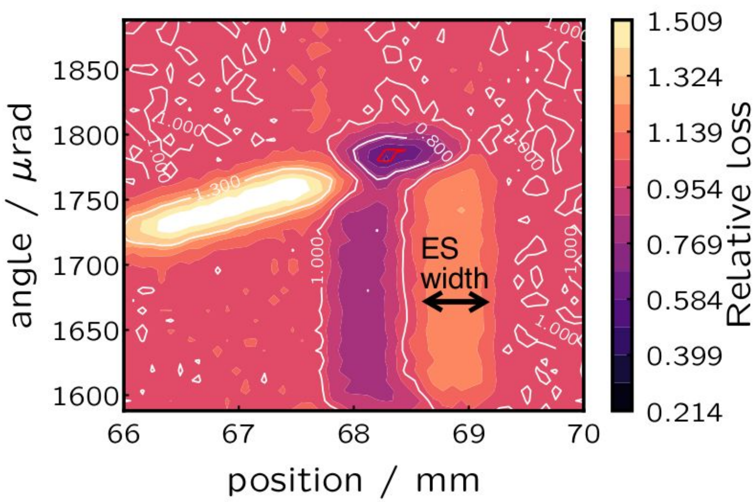
- New TECS installed in LSS4 during YETS 2021/22 [4, 5]:
  - Used as MD device in 2022 with single crystal in CH
  - Aim to make CH operational before end of 2022
  - Multi-crystal VR array to be studied in MD, when available
- How will interlocking be extended to the OP device?
  - Gonio control system will be based on standard collimator system
  - CIBU connection to BIS in BA4 is gonio control rack in BA4 (RA1204)
  - Same interlocking approach to LSS2 TECS as discussed by Mario:
    - SIS interlock on linear position ranges, no interlock on angle
      - HW interlock won't help as LVDT reading not accurate enough to maintain correct angle
    - HW interlock on end-switch (IN/OUT) via BIS to be inverted when devices moves from MD → OP
    - Interlock to be maskable
    - Limit switches and end-stop give hard protection

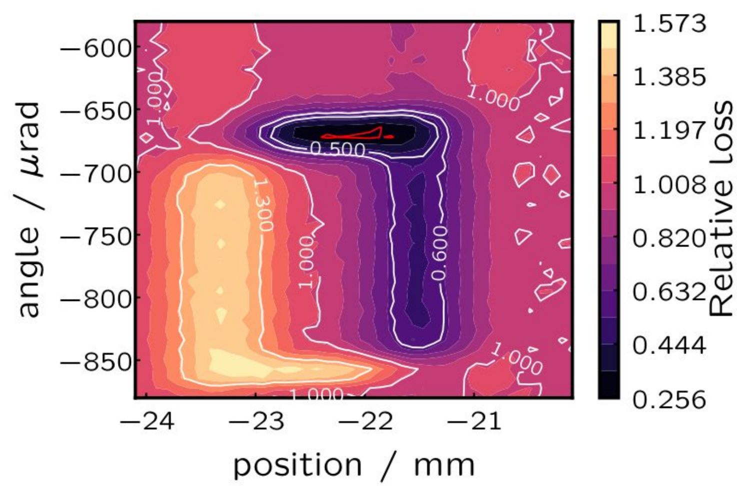
Failure scenarios

- A few vulnerabilities exist at SPS for slow extraction (mainly for protection of ZS):
  - Extraction bumpers (LSS2) and extraction sextupoles are not interlocked by HW (and probably should be)
  - **We recommend an MPP review of SPS slow extraction system in 2021**
- New interlocking possibilities will be available in Run 3:
  - SPS BLM HW interlock on LSS2 **rate** (running sums)
  - SPS BCT HW interlock on **rate** of change of circulating beam intensity
  - **Comment:** LHC BLM's used for MD's will not be ready for interlocking in 2021
- Comments for MPP for TECS (See Mario's slides our interlock strategy)
  - General approach for both TECS in LSS2 and LSS4
  - Most failure scenarios exist presently and are identical to those that risk the ZS
  - Expect the crystal to be far more robust than fragile ZS wire arrays
    - Two crystals tested in HRMT (up to 288 bunched and 1e11 ppb) with no damage and no degradation in the efficiency [6]
    - Crystal was irradiated with 2.4x1e20 450 GeV protons/cm2 in the North Area during one year operation with no damage but with performance deterioration [7]
  - Crystal is positioned far from the circulating beam (and extracted LHC beam)
  - New HW interlocks on rates (beam intensity and loss) protect us against extracting non-resonantly and fast (milliseconds - time constant of bumper circuits)
  - In most cases, if beam-crystal alignment changes (amorphous, AM), the beam loss at ZS will return to nominal (as pre-LS2)

Failure scenarios

Failure	Consequence	Probability	Risk	Mitigation
Crystal-beam angle or positioning error: • Orbit drifts from hysteresis etc. • Error with feedback/forward system? • Crystal actuated towards circulating beam	(i) Loss of shadowing **(slow, t ~ s): channelled beamlet extracted**	**More likely**	**Low:** (i) Revert to nominal beam loss in LSS2	(i) BLM sum (LSS2 and TT20)
	(ii) Loss of shadowing **(slow, t ~ s): channelled beamlet (~10%) impacting ZS wire array**	**Less likely**	**Low:** (i) Beam loss at ZS increased locally by up to ~50% **(slow)**	(i) BLM sum (ZS only)
	(iii) Loss of shadowing **(slow, t ~ s): crystal as amorphous scatter** (iv) Crystal actuated towards circulating beam	**Unlikely**	**Low:** (i) Revert to nominal beam loss in LSS2	(i) BLM sum (ii) Interlock on TECS position (iii) End stop





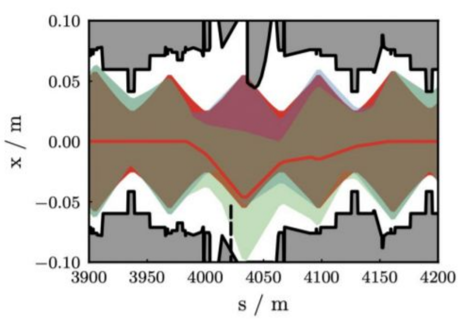
Failure scenarios

Failure	Consequence	Probability	Risk	Mitigation
Extraction bump: • PC no turn-on • PC trip during cycle • Wrong amplitude bump (**SW limits on LSA knob**)	(i) Circulating beam swept into crystal **(fast, t ~ ms): fast extraction of beam (~100%) into TT20 (CH or VR) or onto machine aperture**	**Unlikely** (i) Narrow angular acceptance of crystal	**High**: (i) Targets (ii) ZS damage (in CH)	(i) HW interlock LSS2 bumpers (ii) BCT rate (iii) BLM rate
	(ii) Circulating beam swept into crystal **(fast, t ~ ms): collimation on crystal as amorphous scatterer** (iii) Circulating beam lost on aperture in machine	**More likely**	**High:** (i) ZS damage (ii) Exchange magnets (vacuum chambers)	(i) HW interlock LSS2 bumpers (ii) BCT rate (iii) BLM rate (iv) BLM sum (ZS only)

- ➔ ZS suffered such an accident in 2007, never since (EDMS #1870893)
- ➔ **Comment:** QF glitches were inducing fast extractions (~ ms) to TT20 in Run 2 without any known issue on targets/TCSC

Failure scenarios

Failure	Consequence	Probability	Risk	Mitigation
Multi-crystal array: • Damage or non-conformity after characterisation ... e.g. during transport? • Development of mechanical alignment fault during operation?	(i) Single crystal entering channelling: **(i) Loss of shadowing** **<u>See slide 17</u>**	**Unlikely** (once characterised)	**Low**: (i) Revert to nominal beam loss in LSS2	(i) Characterisi on in H8 (ii) BLM sum (LSS2 and TT20) (iii) BLM ring
Multi-crystal array: • Actuator stuck/blocked in-beam	(i) No impact to LHC beam operation (ii) **<u>if crystal closer than 40 mm to machine axis</u>**	**Unlikely**	**Low**: (i) Possible downtime to SFTPRO	(i) Access needed



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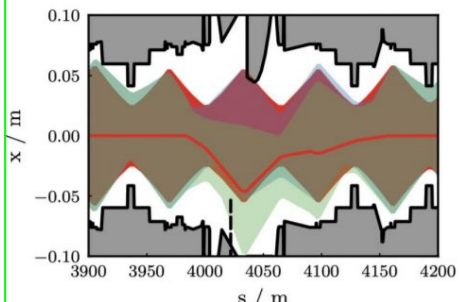

Mechanical switches should not allow this

Procedure in case failure

- When shadowing efficiency degrades the OP team will receive a SIS interlock on beam loss:
  - Normalised (per proton) beam loss thresholds (slow, after cycle played) decided during commission (experience needed to check stability and tighten limits without compromising availability)
  - Procedure:
    - SFTPRO beam cut by SIS
    - Call an ABT expert and analyse event:
      - EN-SMM piquet (or EN-STI expert) called in case of HW issue with TECS
      - If problem understood and resolved, resume operation with TECS
    - Otherwise, retract TECS and resume operation (nominal BLM thresholds)
- Something more serious would trigger a HW interlock (fast trips):
  - This could be BLM above absolute thresholds
  - Procedure:
    - SFTPRO beam cut by HW (fast) HW interlock
    - Call ABT expert and wait before resuming SFTPRO

Summary

- Present interlock system based on beam loss and intensity measured by BLM/BCT will adequately protect the machine:
  - Interlocking on rates of change of beam loss and intensity are available
- TECS in LSS2 to be commissioned as OP device in 2021:
  - Expect to be OP-ready in VR immediately
  - OP-readiness in CH expected later 2021 and depends on efficiency of beam splitting by MSSB in TT20 with beamlet
- TECS in LSS4 to be installed in YETS 2021/22:
  - Initially as an MD device with OP-readiness expected later 2022
  - Interlock strategy identical to LSS2 TECS
- Independent of the TECS installation we propose an MPP review of the SPS slow extraction system
- ECR for LSS4 TECS installation to be circulated early 2021