Crystal shadowing for loss reduction

ACN2020 - Applications of Crystals and Nanotubes for Acceleration and Manipulation (EPFL)

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Outline

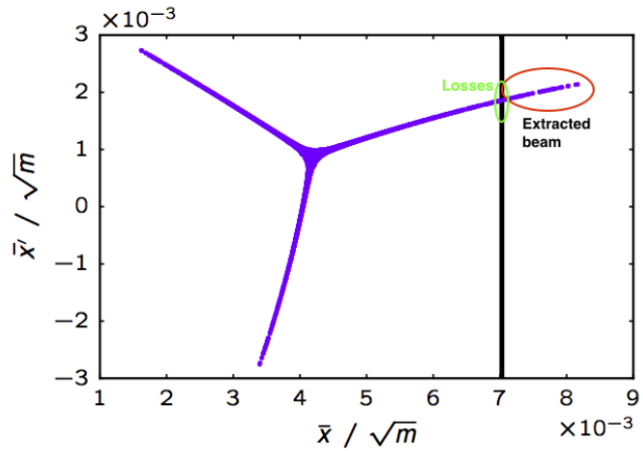
Introduction
- Si bent crystals
- ES shadowing concept
- Angular spread at the SPS

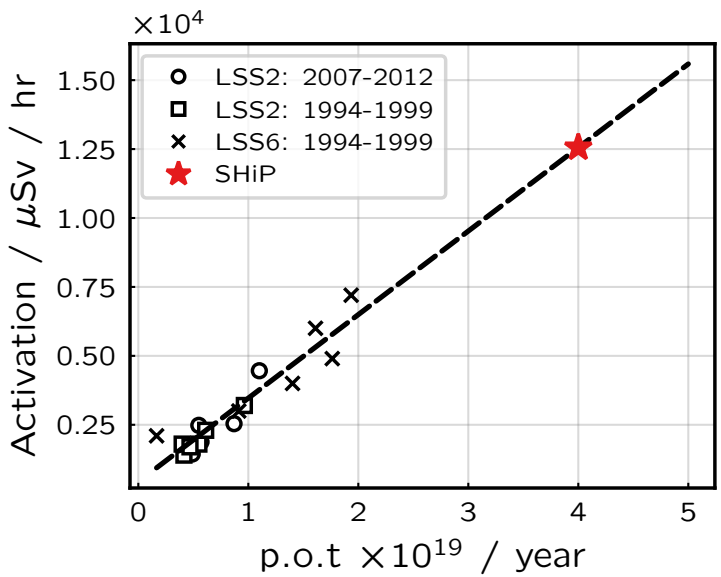
Crystal shadowing of the SPS-ZS
- Local shadowing
- Proof of concept in the SPS
  - Local shadowing measurements
  - Stability and transport
- Non-local shadowing using CH
- Non-local shadowing using MVRA
- Combination of different loss reduction techniques

Summary and outlook

Introduction

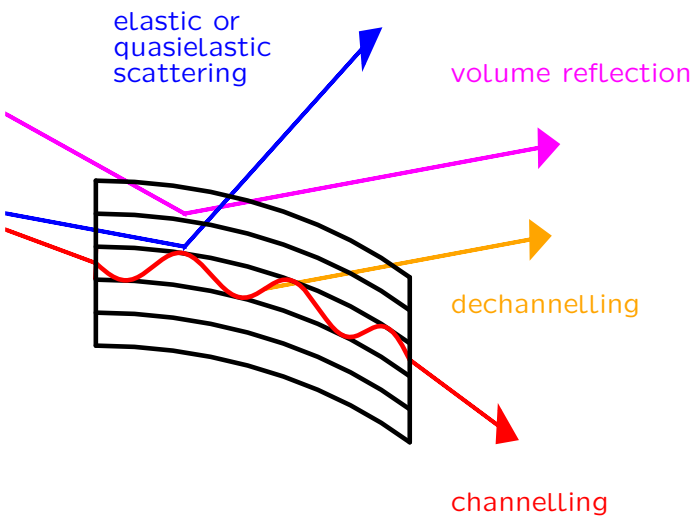
- The CERN Super Proton Synchrotron (SPS) physics program is dominated by the slowly extracted protons delivered to the experiments in the North Area (NA)
- Slow extraction, based on third-integer resonance, comes with unavoidable losses at the electrostatic septum (ES, or ZS for the SPS)
- Continues flow of particles from beam core to large amplitudes following (almost) straight separatrix
- ES thin wires are responsible for separating the extracted from circulating one $\Rightarrow$ direct exposure of wires to primary particles!
  - About 3% of the circulating beam is lost in the slow extraction channel
  - This is the main limiting factors to the deliverable protons on target (POT) from the SPS
- Since a few years, a significant research effort is ongoing at CERN to try to mitigate the losses during slow extraction to reduce the dose to personnel in case of intervention
- Future proposed experiments like SHiP (Search for Hidden Particles) at the SPS Beam Dump Facility (BDF), will request about four times the number of protons extracted from the SPS in one year $\Rightarrow$ 4×10^{19} protons/year

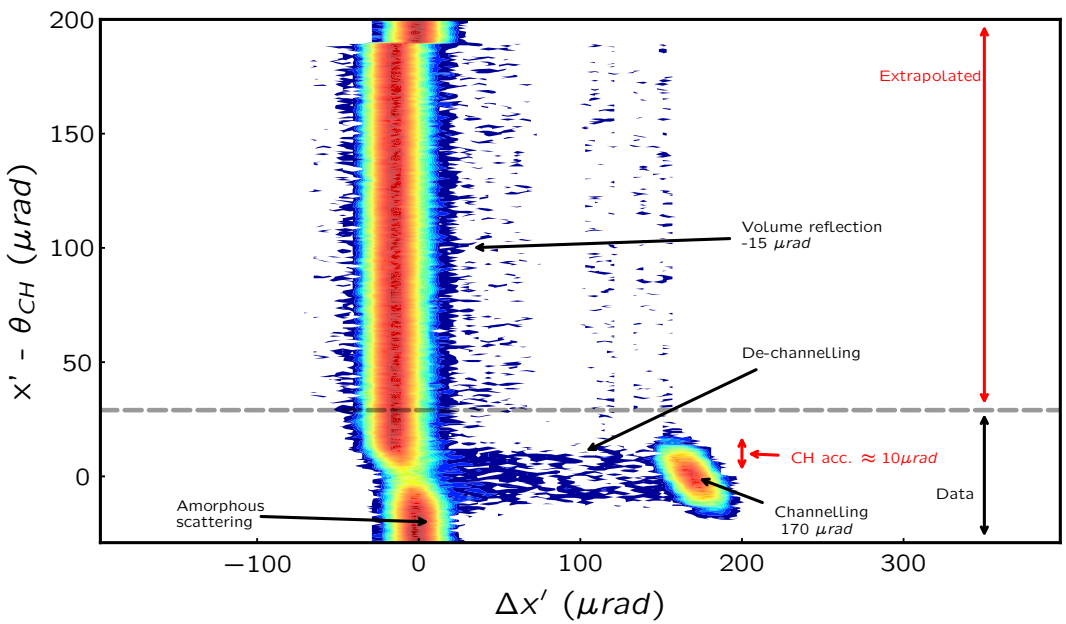




Si bent crystals

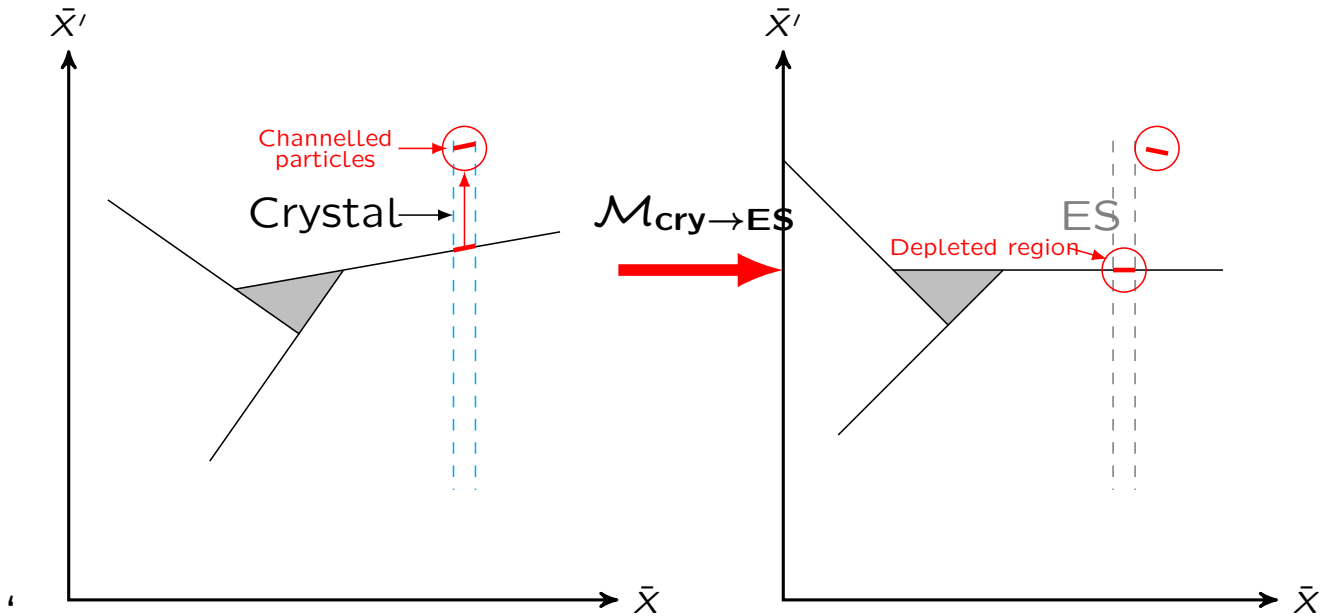
- Si bent crystals seem to have all the needed characteristics to be used as loss reduction devices for slow extraction
- For example, a single 2 mm long crystal can deflect 400 GeV protons by 170 µrad ⇒ this corresponds to ≈120 T magnetic field!
- They can be made very thin, deal with large intensities [1, 2, 3] and have low probability to perform inelastic interactions [4] (⇒ low losses)
- For the following tracking simulations, interaction of charged particles with crystals done using empirical 2D-pdf (obtained from UA9 measurements) and treated as source of single kick (no inelastic interactions considered)





ES shadowing concept

- A thin bent crystal is placed to $n \times \pi + \Delta\mu$ 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 $\Rightarrow$ we called this **septum shadowing** [5, 6]
- After the success of the 2018 measurements of loss reduction at the SPS with a passive diffuser [7], we installed a crystal in the SPS to test this concept



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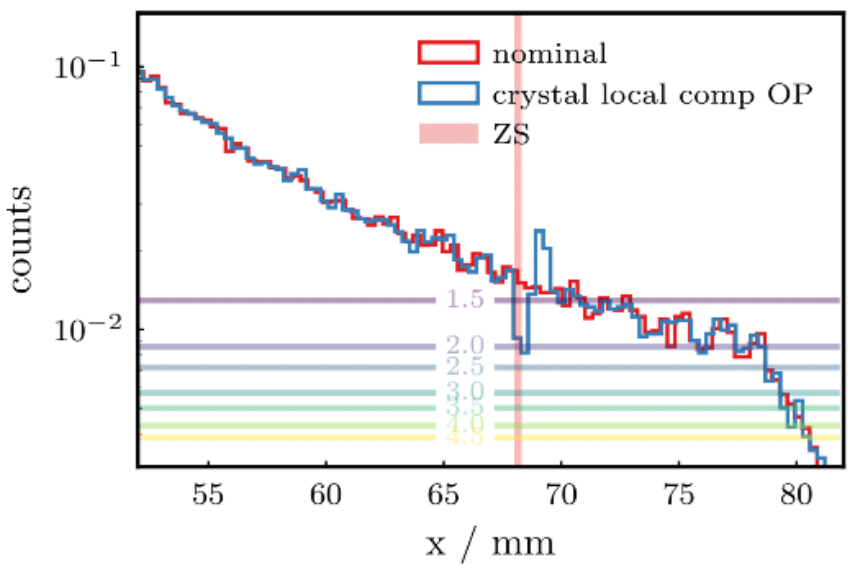
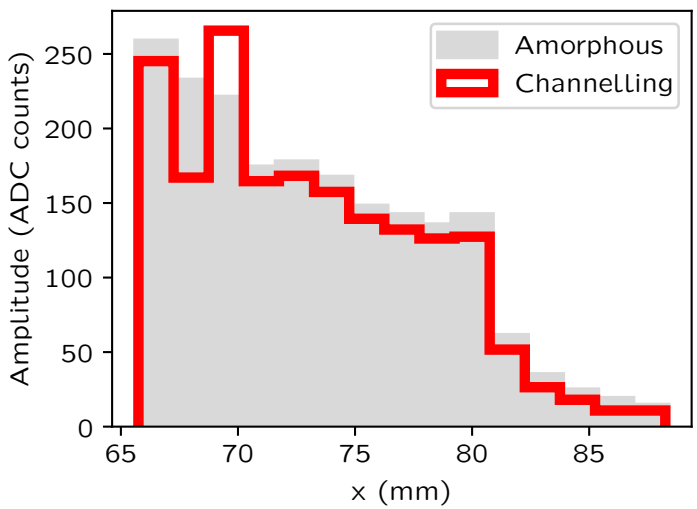
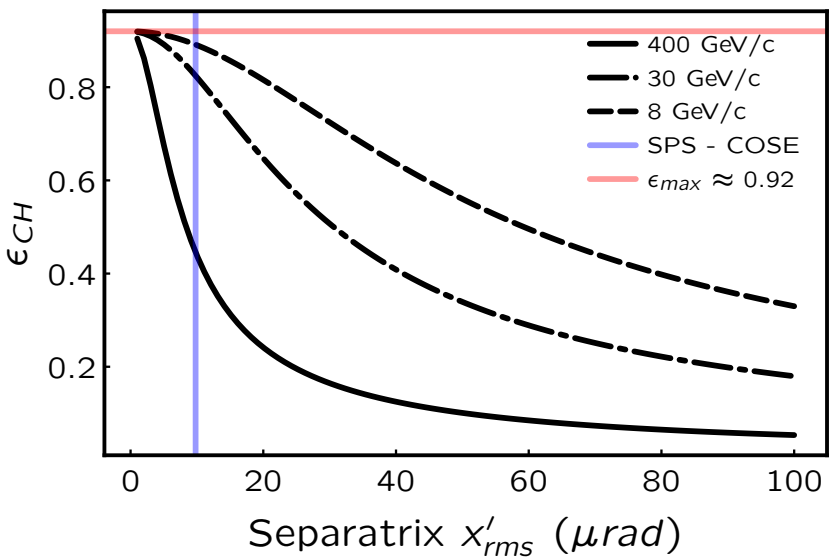
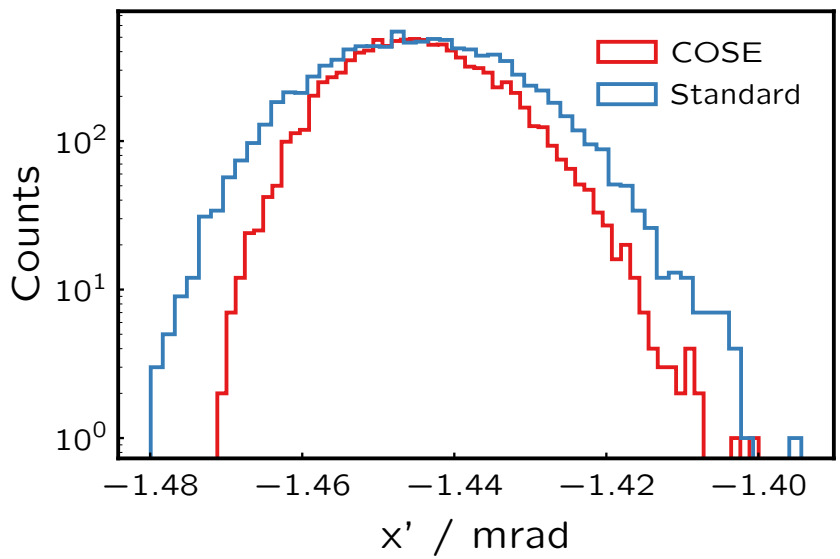




Angular spread at the SPS

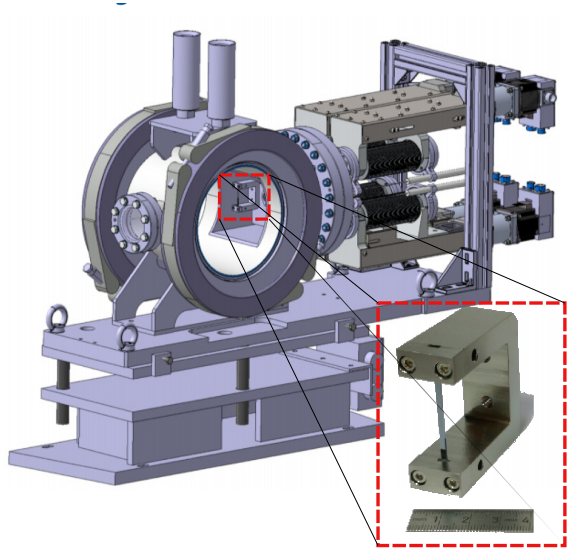
- The crystal CH angular acceptance (RMS), from measurements, is $\sigma_{\theta,CH} = 5.4\,\mu\text{rad} \approx \theta_c/2 = \sqrt{2U_{max}/pv}/2$
- As the CH angular acceptance is essentially the critical angle, and this goes as $1/\sqrt{p}$, it is tiny for the SPS...
- The angular spread was reduced of about 20% using **COSE** (a recently developed technique [8] to optimise resonant slow extraction) $\Rightarrow$ from 12.3 µrad to 9.8 µrad
- We can see how sensitive this is for the SPS case (other energies obtained as simple $1/\sqrt{p}$ scaling)

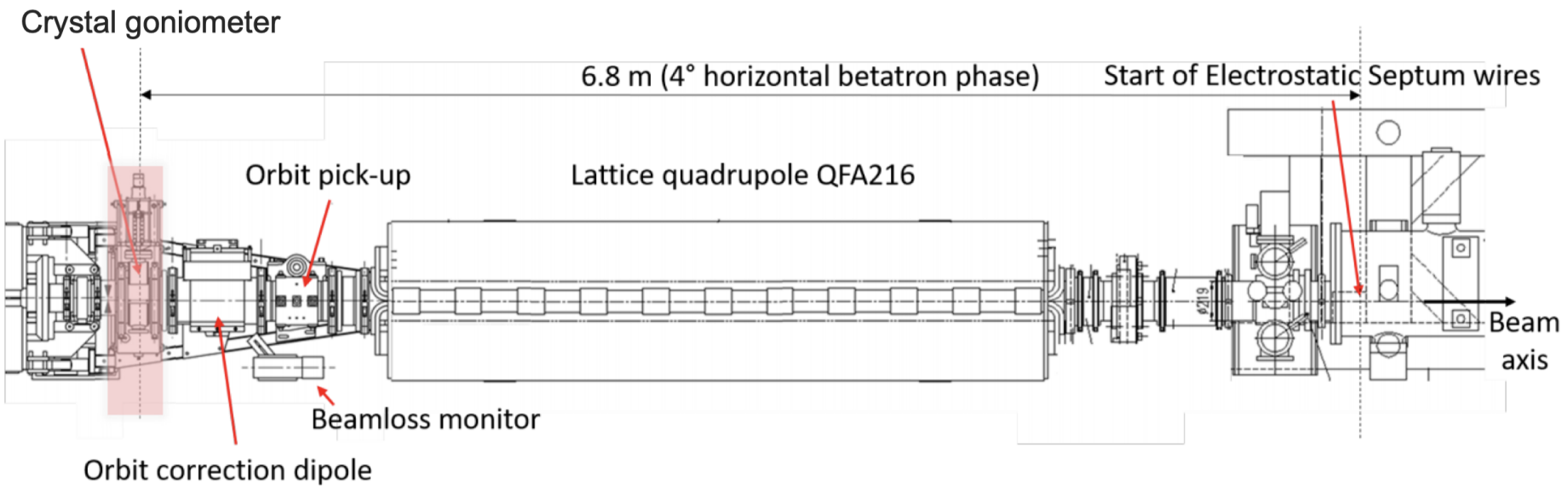




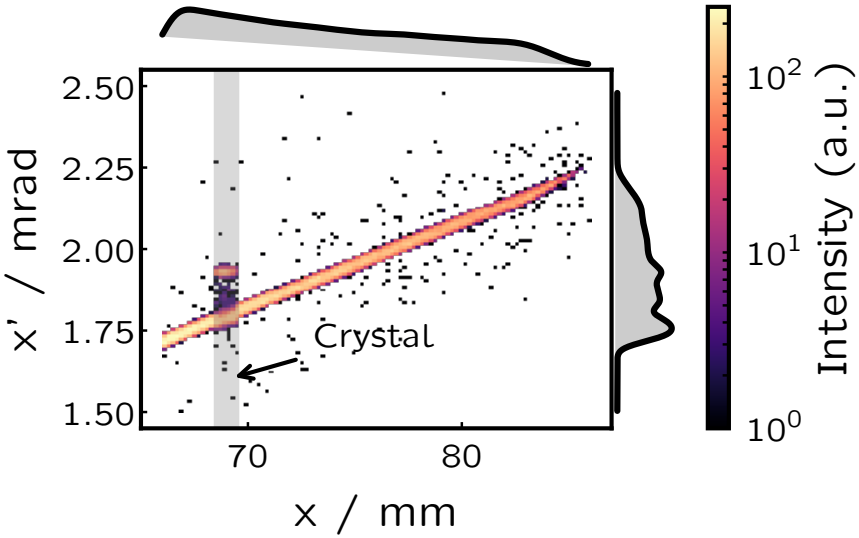
Local shadowing of the SPS-ZS

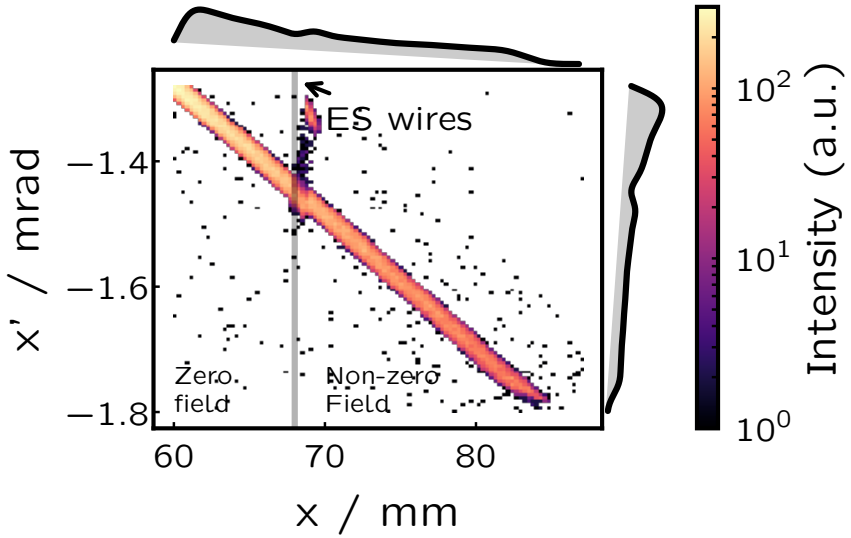
- A goniometer with the specified crystal characteristics was installed in the SPS
- The total tank length is only 187 mm!
- The very short device was developed with UA9 and installed 7 m upstream the beginning of the ES
- The crystal itself is 0.8 mm thick and 2 mm long for a vertical extension of 35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





Tracking simulations for shadowing





- Simulations done using PTC high-order maps (via *maptrack*) + *pycollimate*. There was the need to speed up element by element tracking simulations to perform the scans that will follow
- The relative phase-advance between crystal and ES is about 4°
- A large CH angle needed to help push particles away from ES wires: there is not so much position gain otherwise
- ES thickness used for all the following simulations is 500 µm (thickness that best reproduces measurements, see later for details)

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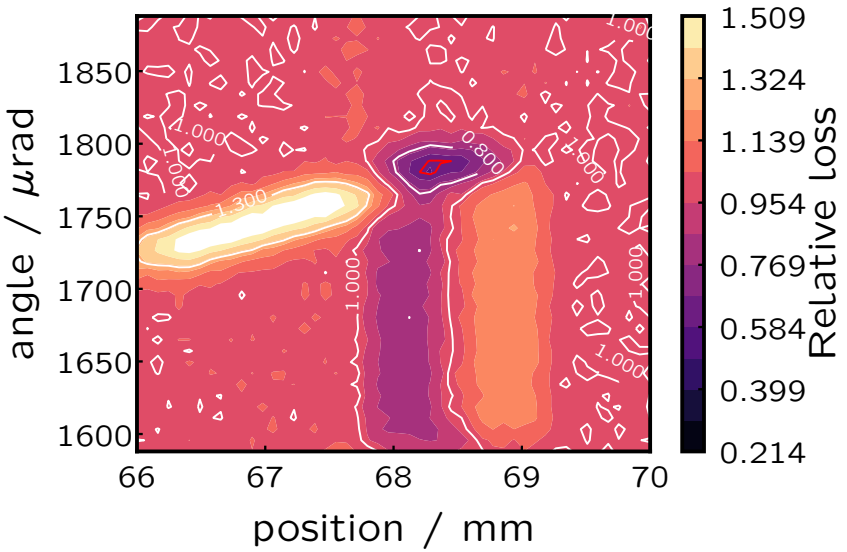

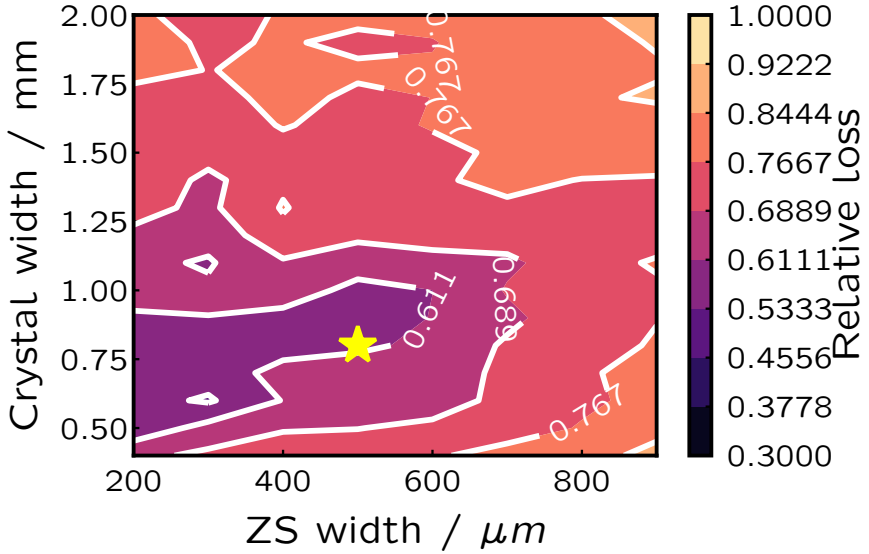

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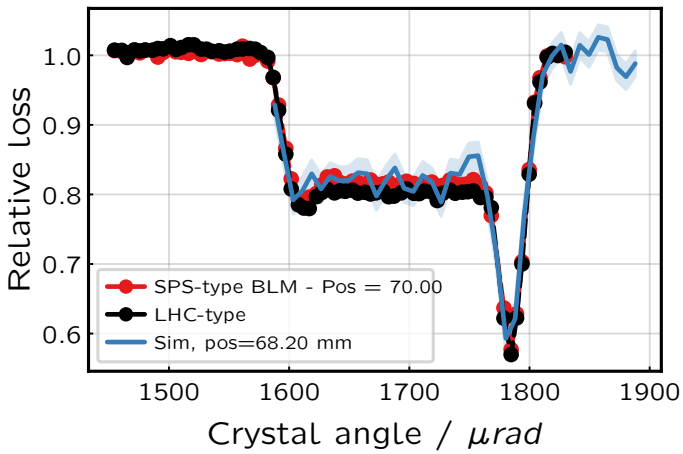

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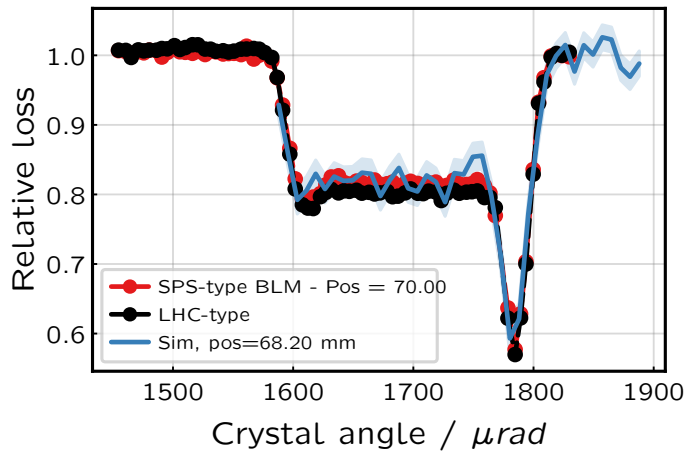

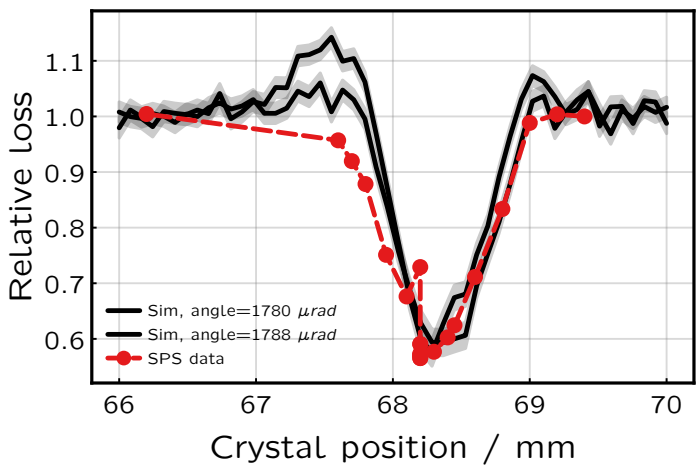

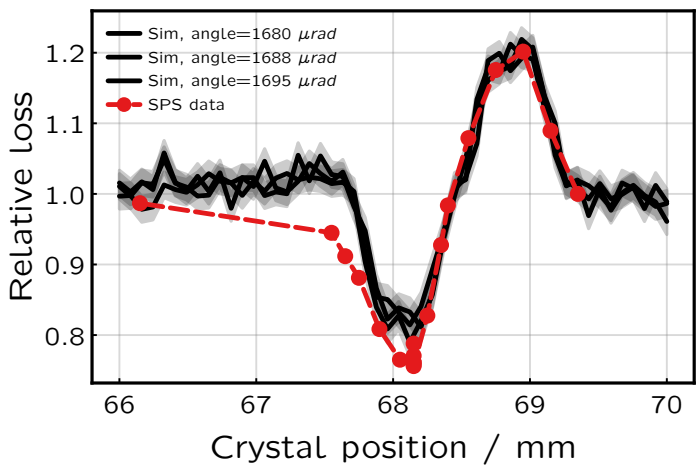

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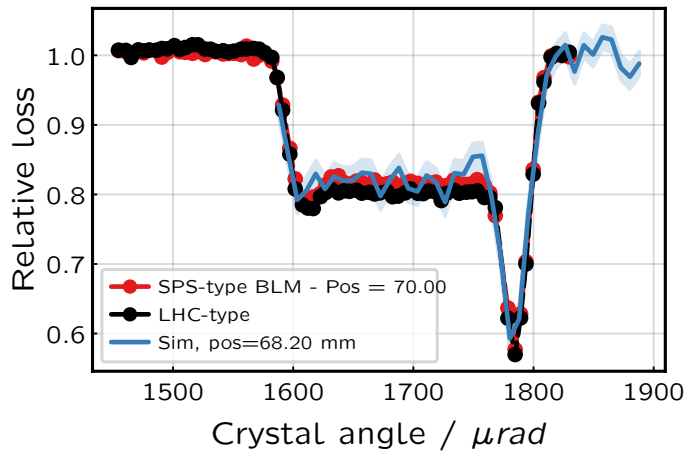
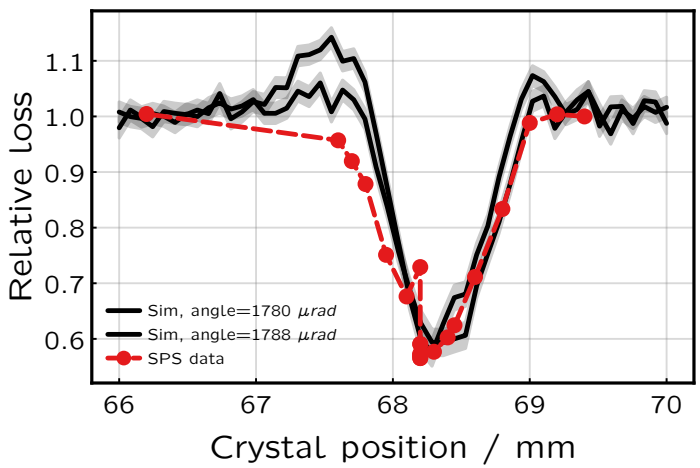
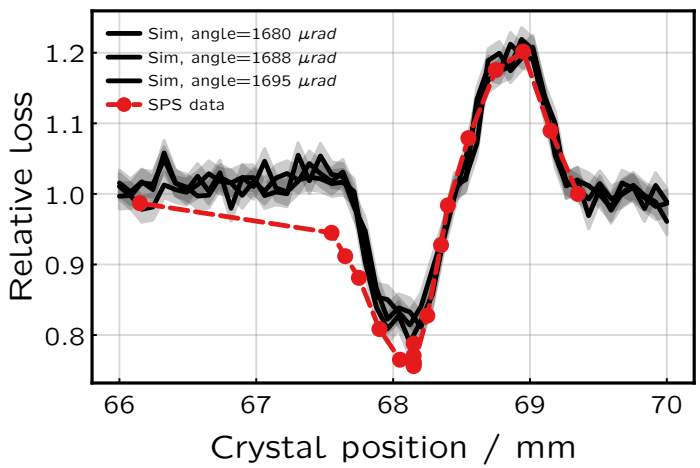
- Linear scans in VR and CH were also performed (or reconstructed from angular scans) ⇒ the loss increase is de facto a fine scan of the ES effective width!
- The very good agreement between measurements and simulations was achieved using an automatic optimiser for the angular spread distribution after optimisation of ZS width ⇒ 500 µm in agreement with diffuser studies...

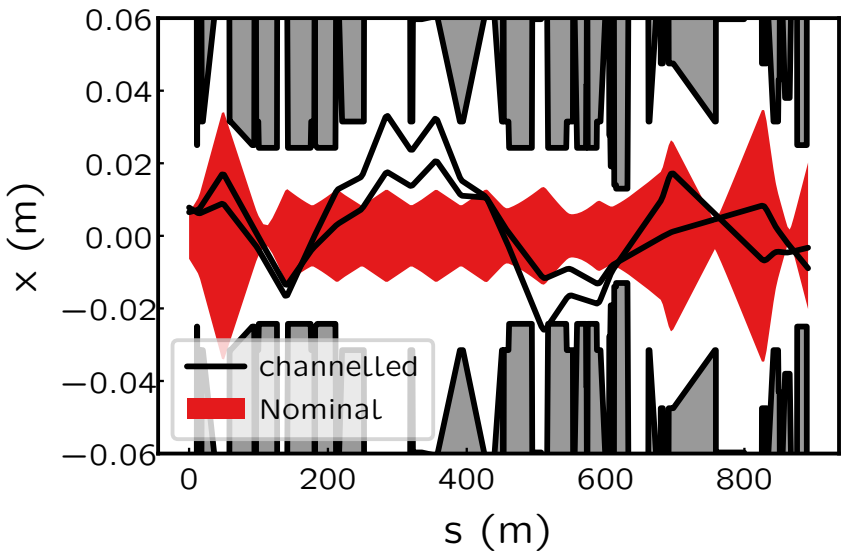


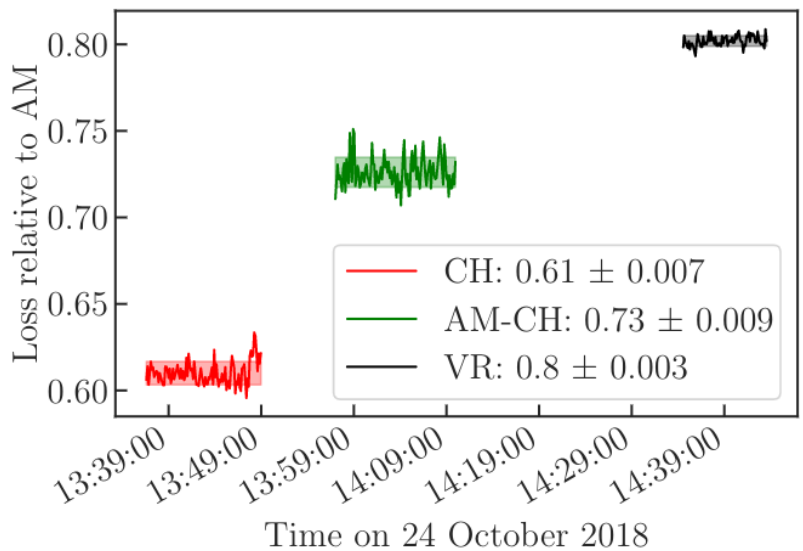




Stability and transport in the line

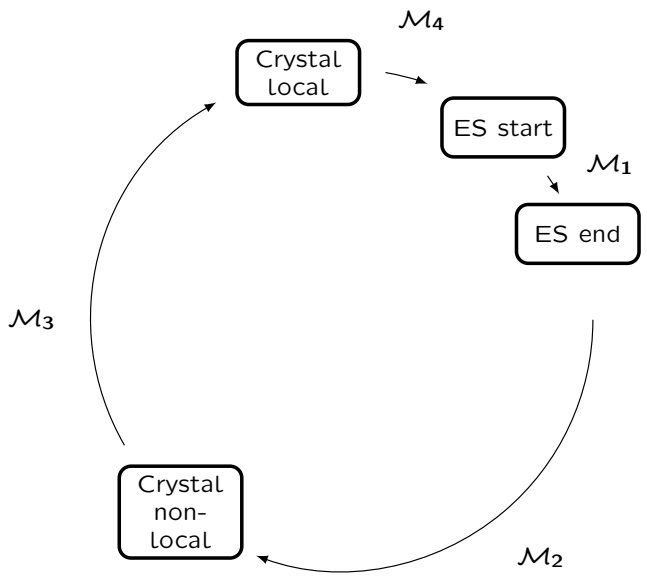
- It was not easy to transport the channelled beam down the transfer line - initially, losses at quadrupole (as expected from simulations) were dumping the beam making impossible to evaluate CH stability
- Due to the different initial conditions of the channelled beam, large oscillations in TT20...needed local bumps to be able to propagate it through the TL and reach the target (or the splitter)
- Stability test could then be carried out - loss reduction in both CH and VR very stable for about 10-15 minutes each
- Test on operational beam also carried out for 13 hours in VR - **stable loss reduction of about 20% with** 2.8×10^{13} p $\Rightarrow$ dediced to use it operationally in VR at the restart in 2021 (in CH only if solution for transport found)





Non-local shadowing of the SPS-ZS

- Further optimisation of loss reduction can be achieved playing with the crystal position in the SPS lattice
- Thicker crystal, 1.8 mm, needed to maximise the loss reduction
- The chosen position, in Long Straight Section (LSS) 4, close to MSE.4 (extraction tick magnetic septum), has the following advantages:
  - High energy bumpers available (not enough strengths on CODs at 400 GeV)
  - About 180° phase-advance from ES $\Rightarrow$ negative bump hence no interference with fast extraction elements of LSS4
  - 2 extraction sextupoles between the crystal and the ES $\Rightarrow$ large gain for angle to position transformation, this is key to reach large loss reduction!



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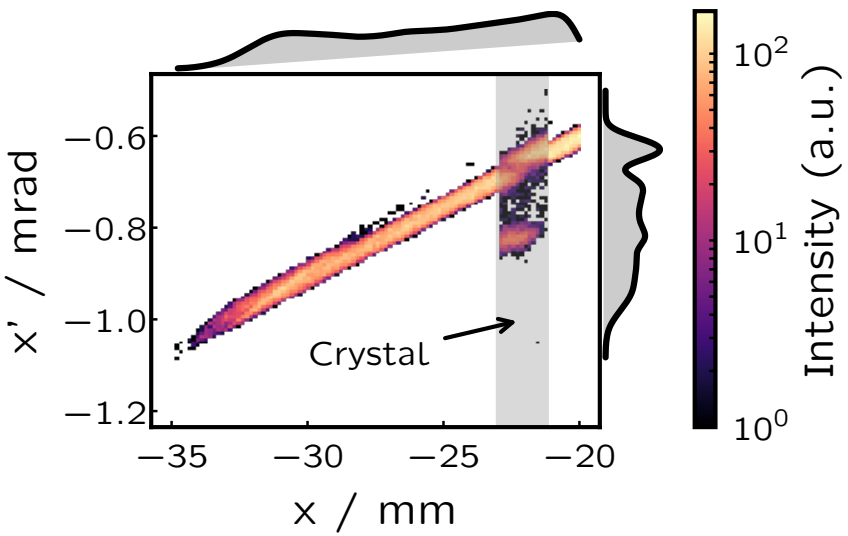
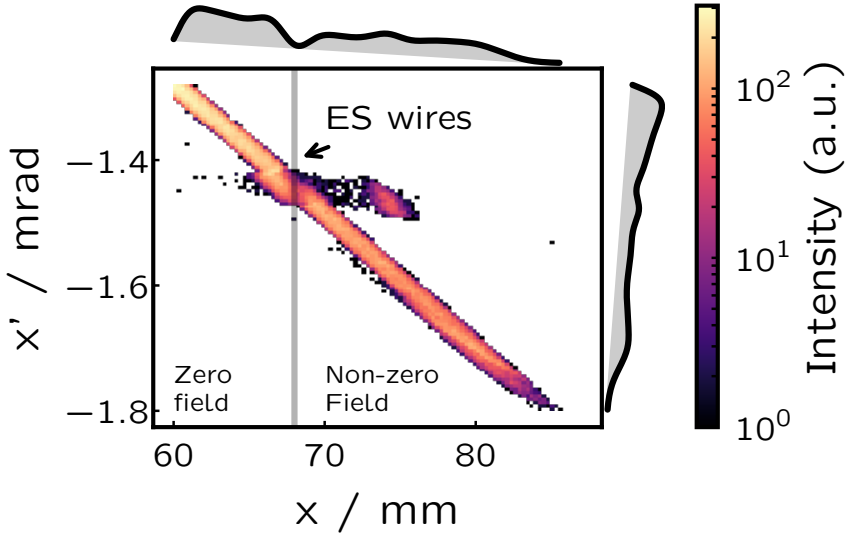
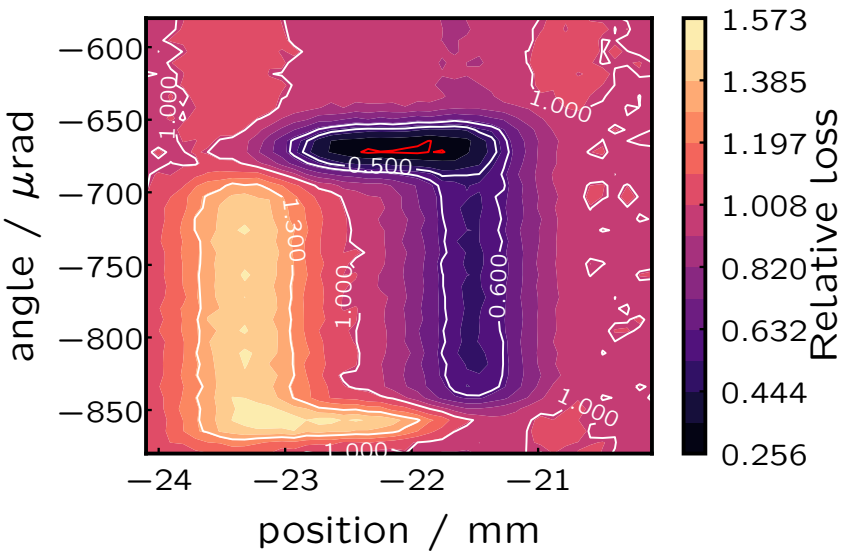
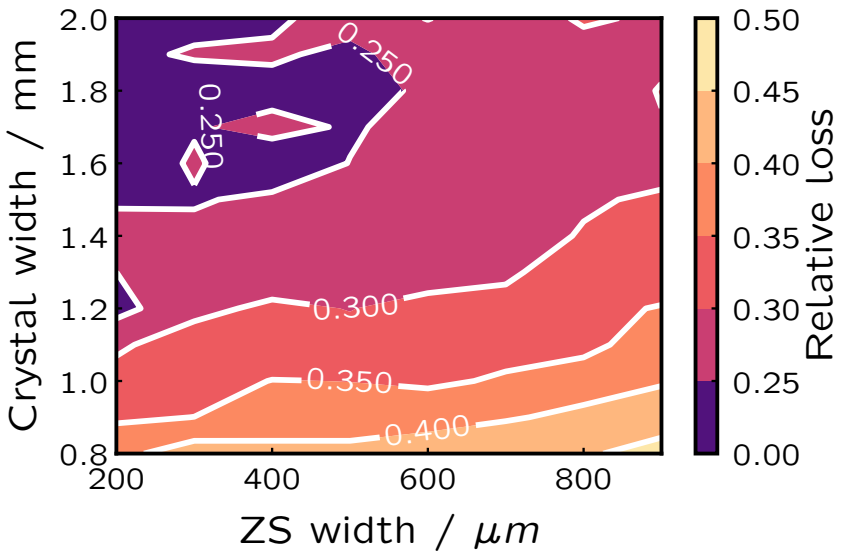




- The relative phase-advance between crystal and ES, in this case upstream of QFA.418, is about $n \times 180 + 12°$ (where n is odd)
- This is basically the same as the local case, but thanks to the amplitude detuning introduced by the strong extraction sextupoles between crystal and ES the gain in position is much larger
- This gives smaller emittance for the extracted beam

Tracking simulations for shadowing

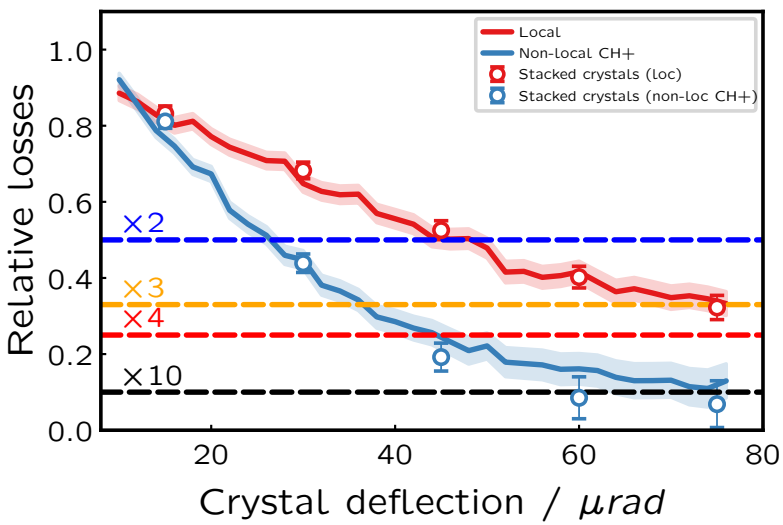


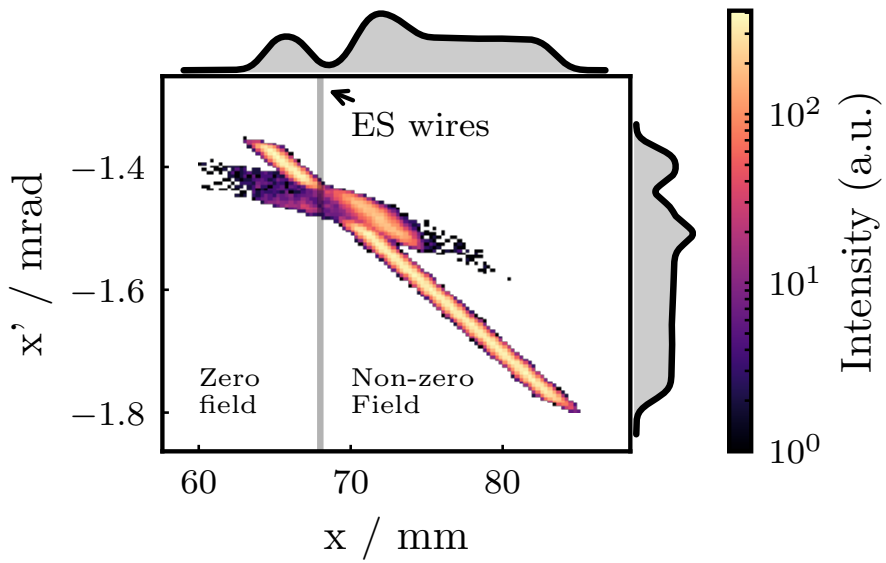


- A max reduction of about 75 % is achieved by placing a 1.8 mm thick crystal in LSS4 close to the QFA.418
- Up to a ZS thickness of about 500 µm, a 1.8 mm thick crystal is needed to guarantee the factor 4 reduction...

Non-local shadowing - Multi VR array

- An even further optimisation is to use Multi Volume Reflection Array (MVRA) crystals
- The main advantage is the exploitation of the high efficiency of VR phenomenon $\Rightarrow$ the efficiency of 5 crystals becomes about $\epsilon_{TOT} \approx \epsilon_{VR}^5 = 0.98^5 = 0.9$
- Using the same simulation setup and assumptions as just described, it is predicted **$\times$10 loss reduction!**
- Aiming to install it in the SPS for proof-of-concept in 2022





Comparison between different shadowing

Local Shadowing

- Maximum possible loss reduction using single crystal in CH $\Rightarrow$ 44% (measured!)
- Crystal in the same CO bump as ES - operationally simpler
- Large deflection from crystal needed to be able to jump the ES wires (minimum angle to guarantee about x2 reduction is 120 µrad)
- **Large emittance of the extracted beam**
- Very thin crystal (0.8 mm), hence very low local activation

Non-local Shadowing CH

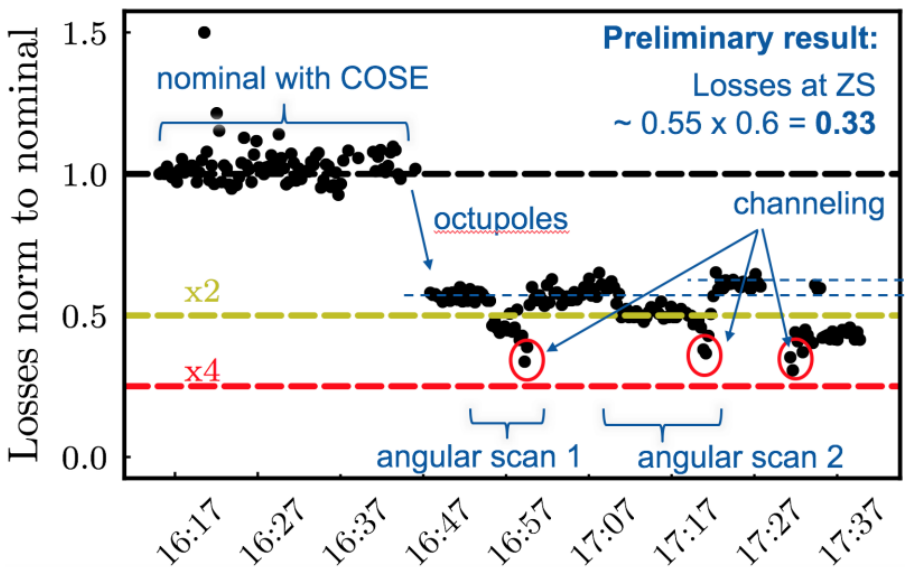
- Maximum possible loss reduction using single crystal in CH $\Rightarrow$ 75% (only simulations)
- Crystal has dedicated CO bump - need to set up 2 separated bumps at the same time
- Loss reduction almost insensitive to maximum CH deflection (can go down to $<$70 µrad and still have the same reduction factor)
- More compact extracted beam envelope $\Rightarrow$ **easy to transport in the transfer line**
- Thicker crystal (1.8 mm)

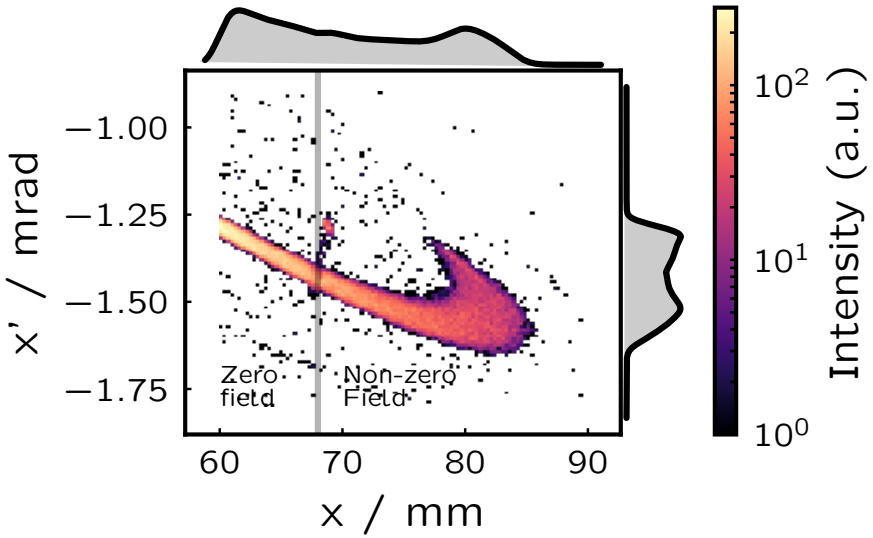
Non-local Shadowing VR

- Maximum possible loss reduction using MVRA $\Rightarrow$ 90% (only simulations)
- Crystal has dedicated CO bump - need to set up 2 separated bumps at the same time
- **Much more compact extracted beam envelope**
- Thick crystal (1.8 mm) and very new technology!

Crystal + octupoles: very preliminary MD results

- Combined two loss reduction methodologies: crystal shadowing + separatrix folding [9]
- Results are already very encouraging, although optimisation still needed...first of all in simulations!
- High performance simulations needed to perform parametric scans in these highly non-linear conditions...ongoing.





Summary and outlook

- Very thin Si bent crystal installed in the SPS in mid-2018 as proposed for slow extraction loss reduction
- **Loss reduction measured up to 44% with beam** and reproduced in simulations (very good agreement shown for ES width of 500 µm)
- Non-local version of crystal shadowing in CH proposed and **possible 75% loss reduction predicted in simulations** (assuming same ES width...)
- Non-local version of crystal shadowing **using MVRA proposed and possible 90% loss reduction predicted in simulations** (assuming same ES width...)
- Operational deployment of local shadowing foreseen at restart in 2021
- Work ongoing to install a MVRA for non-local shadowing during next run
- Work is also ongoing to exploit numerical optimisers and machine learning algorithms to automatise the shadowing setting up
- **Loss reduction target of x4 for SPS slow extraction for future operation seems in reach!**

Thank you!

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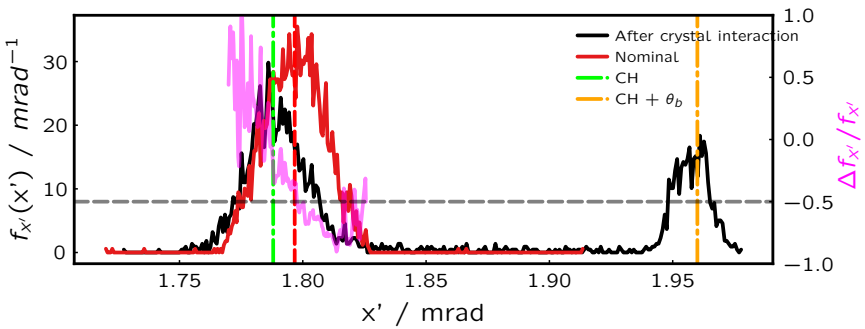
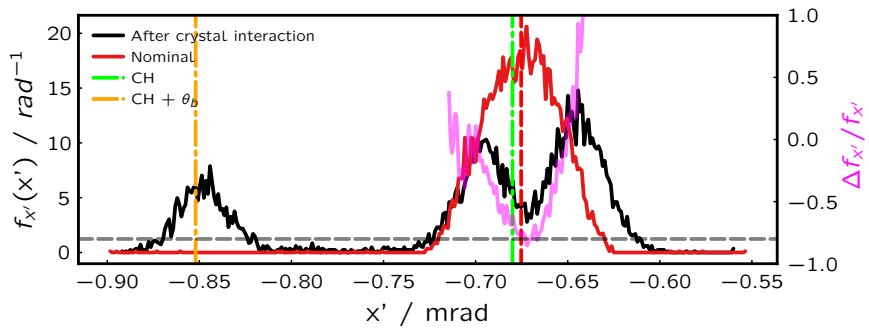
Backup

Why non-local shadowing gives ×4 loss reduction?

- The angular spread of the beam seen by the crystal depends on the separatrix orientation (phase-advance from the ZS), local separatrix angular spread and crystal thickness
  - At the "local" position, the total angular spread seen by the crystal is ≈ 60 µrad
  - At the "non-local" position, and due to the 1.8 mm thickness, the total angular spread seen by the crystal is ≈ 100 µrad

  ⇒ This means that also VR and AM scattering play a significant role in the overall loss reduction that the crystal can provide ⇒ **Crystal orientation is also fundamental to fully exploit this effect!**





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- The angular spread of the beam seen by the crystal depends on the separatrix orientation (phase-advance from the ZS), local separatrix angular spread and crystal thickness
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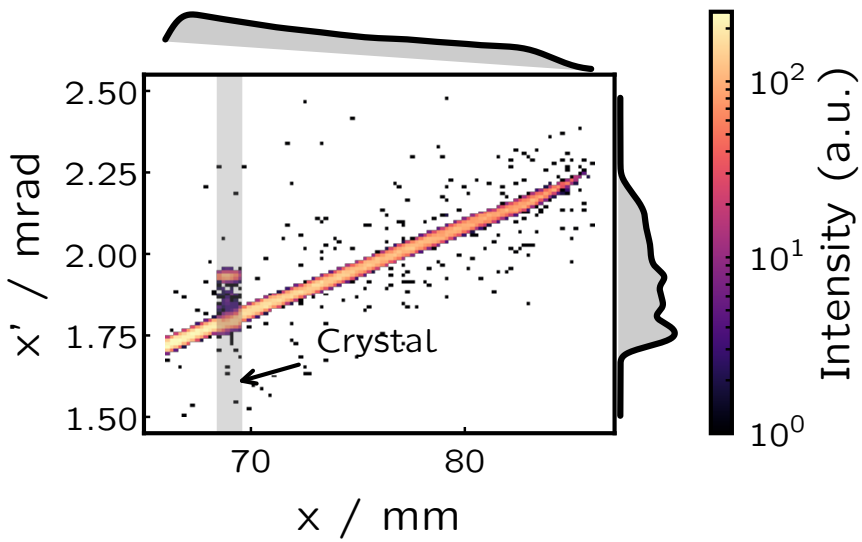
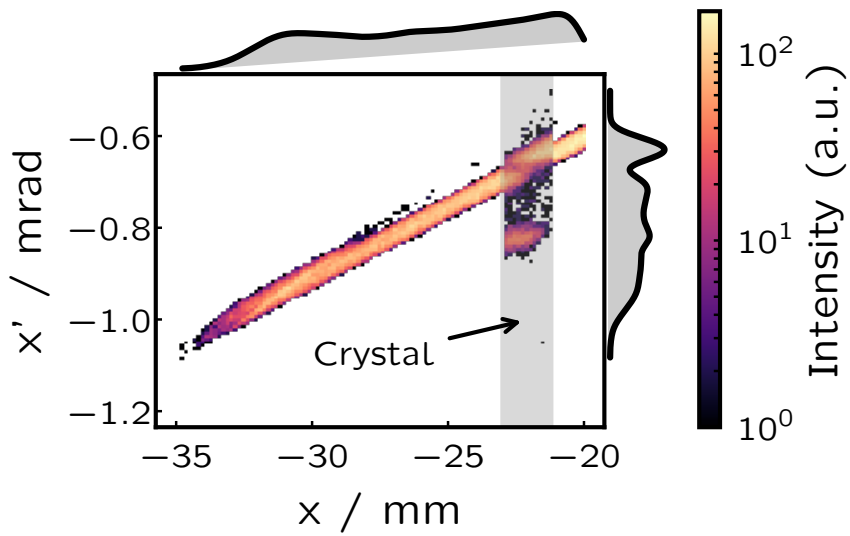
  - ⇒ This means that also VR and AM scattering play a significant role in the overall loss reduction that the crystal can provide ⇒ **Crystal orientation is also fundamental to fully exploit this effect!**
- We saw what it can be the maximum density reduction only looking at the angular distributions at the crystal ⇒ this of course needs to be translated into position!





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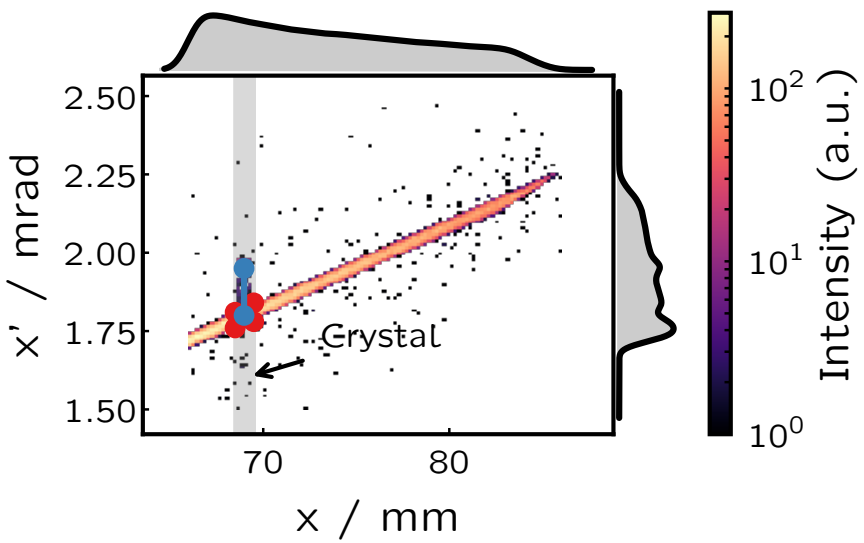
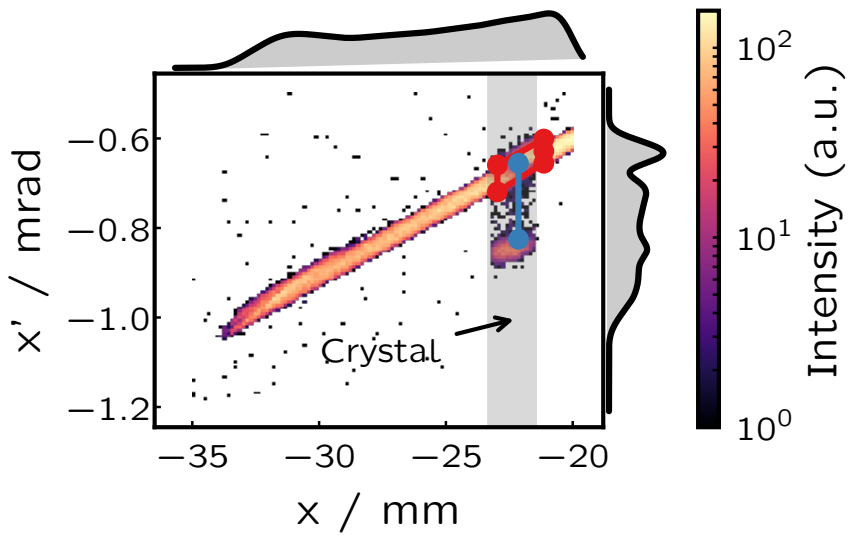
- To do this, we can look at a simple model only considering the part of the separatrix interacting with the crystal and then track it to the ZS





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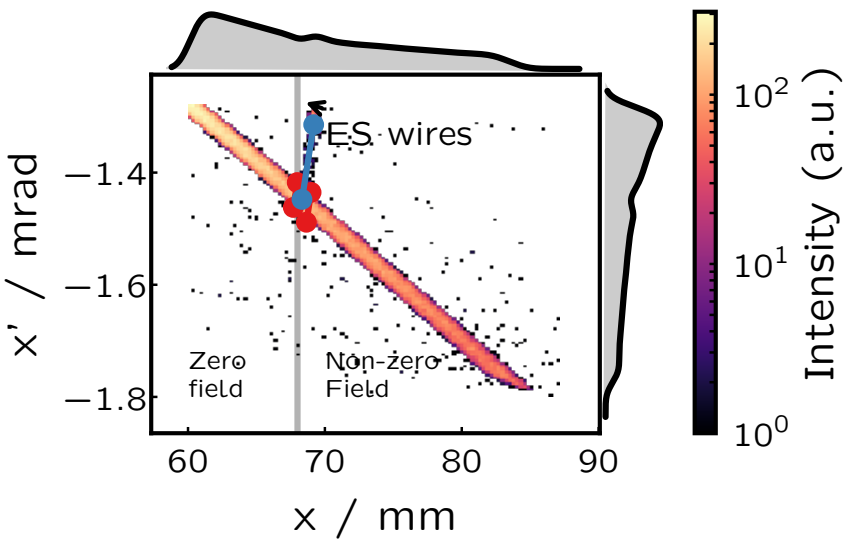

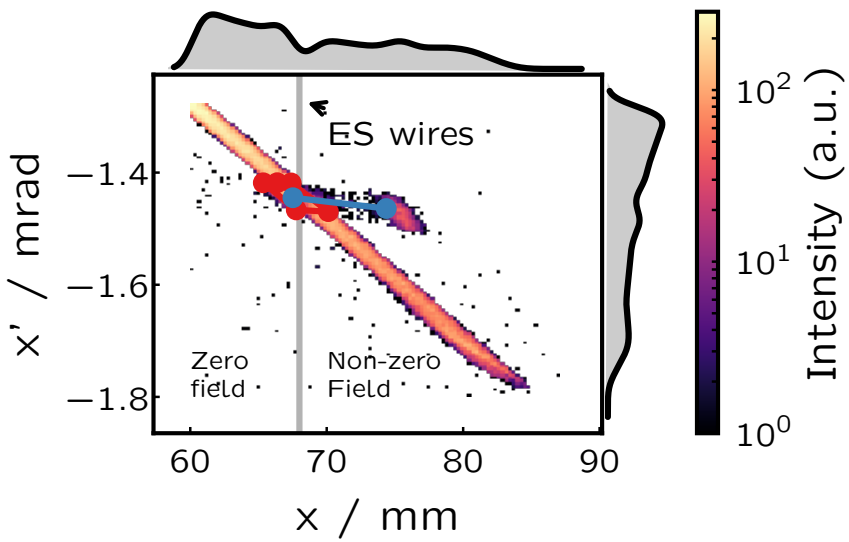

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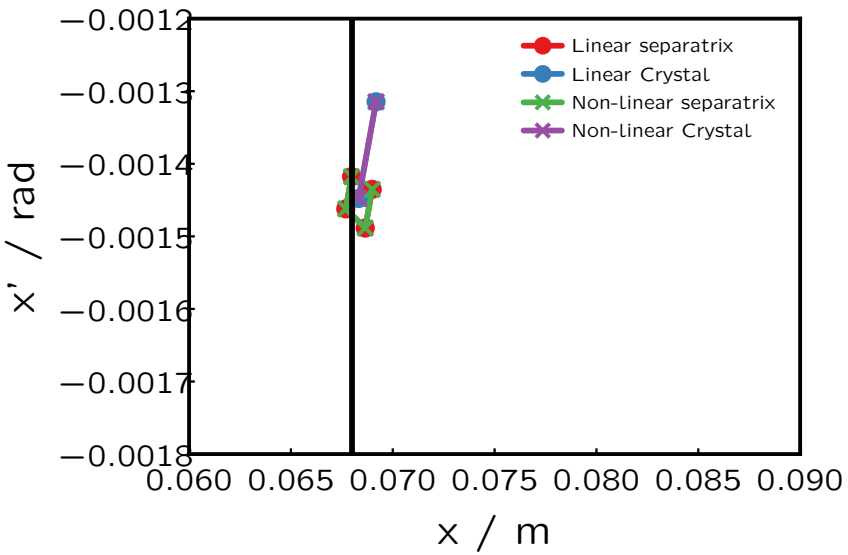
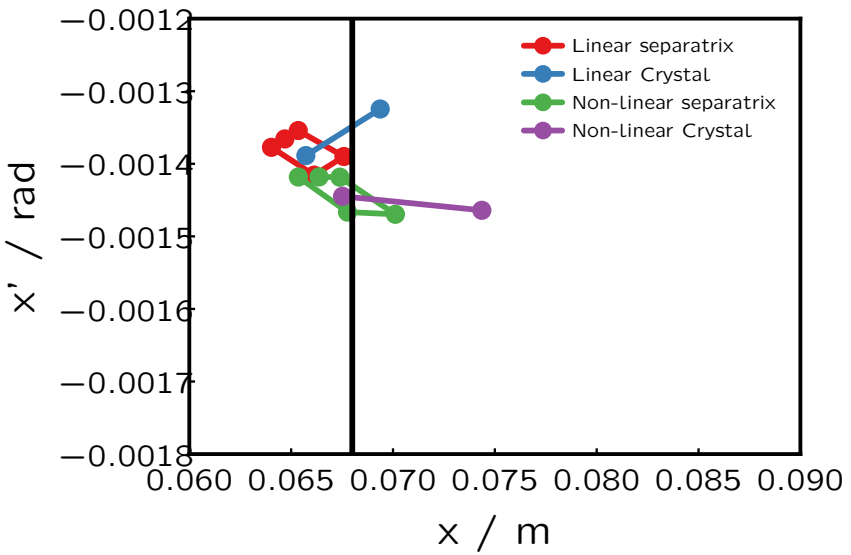
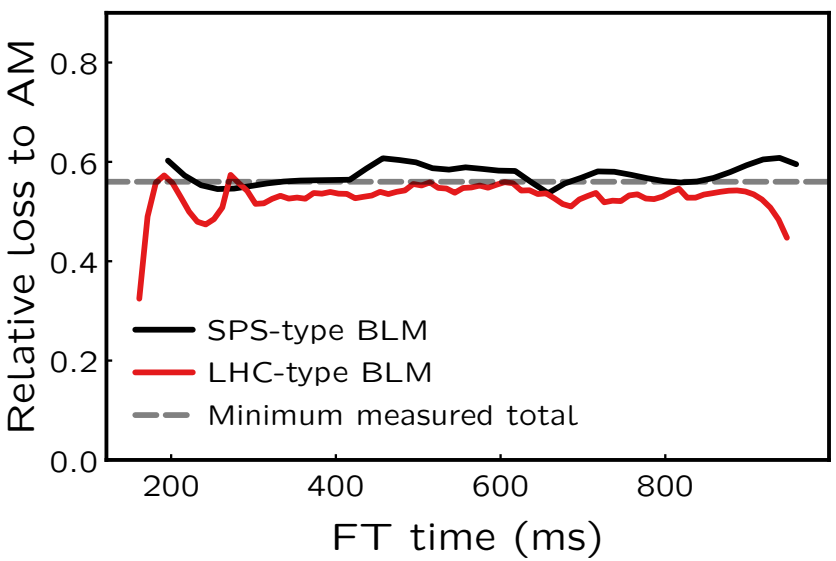
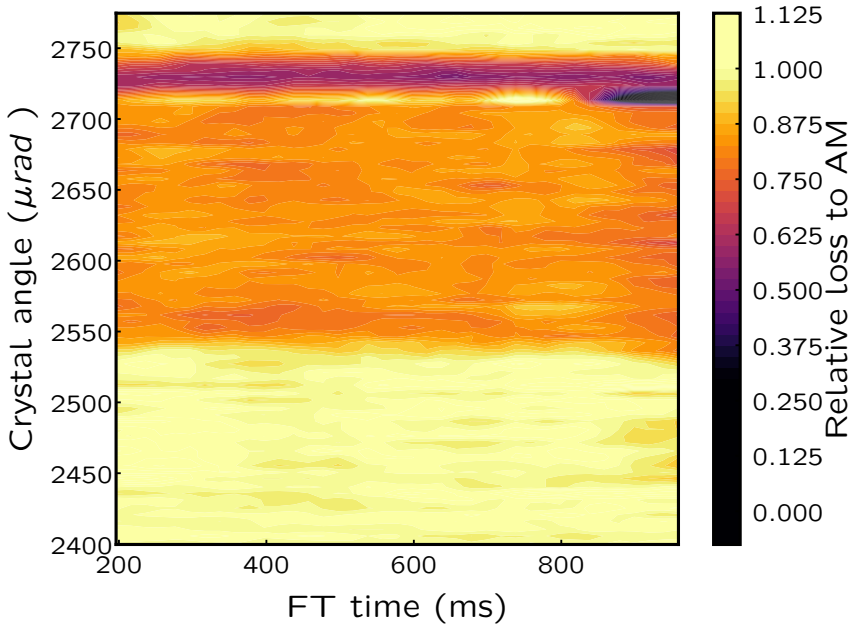
- To do this, we can look at a simple model only considering the part of the separatrix interacting with the crystal and then track it to the ZS
- Then comparing with a simple linear rotation from crystal to ZS, it is clear how **the non-local location profits enormously from the strong harmonic sextupoles between crystal and ZS** $\Rightarrow$ **we can basically reach an equivalent of almost $\Delta\mu_x \approx \pi/2$!**





Loss reduction along the extraction - COSE vs QSWEEP

- We also measured loss reduction as a function of time (during spill essentially)...
- It is very instructive to see a significant difference between the time evolution of losses between COSE and QSWEEP...proving the effectiveness of the separatrix control methodology (see Verena's talk)!