Crystal shadowing for loss reduction

ICFA Mini-Workshop on Slow Extraction 2019

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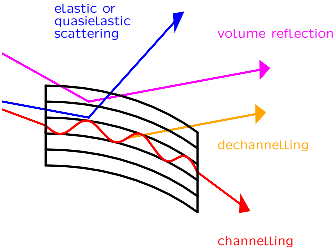
Outline

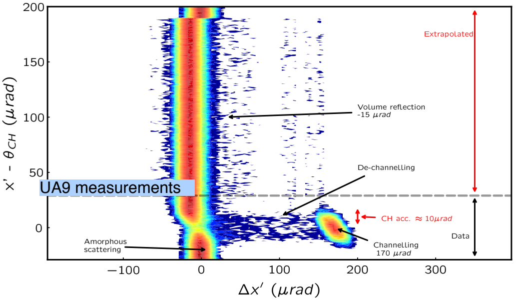
Introduction

- 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 ⇒ direct exposure of wires to primary particles!
  - At the SPS, as already discussed, we have about 3% of the circulating beam lost in the slow extraction channel
  - This is the main limiting factors to the deliverable protons on target (POT) from the SPS
- As already seen also at the last WS, the presented passive diffuser scheme to shadow the ES wires can be powered up using Si bent crystals
- In 2018, after the successful test with the passive diffuser in the SPS, we installed an ad-hoc goniometer and crystal for the shadowing concept
  - We present here: simulations, measurements and possible outlook for such a loss reduction concept

Si bent crystals

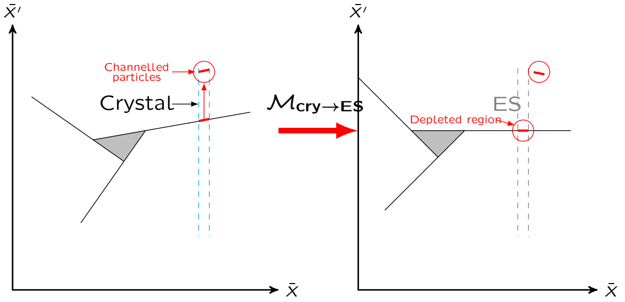
- Si bent crystals seem to have all the needed characteristics to be used as loss reduction devices for slow extraction
- For example, a single 2 mm long crystal can deflect 400 GeV protons by 170 µrad ⇒ this corresponds to ≈120 T magnetic field!
- They can be made very thin
- They can deal with large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





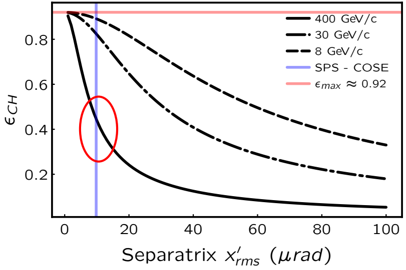
ES shadowing concept

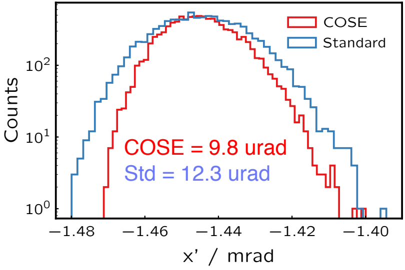
- A thin bent crystal is placed to $n \times \pi + \Delta\mu$ from the ES (n integer and $\Delta\mu$ sufficiently large to fit ES wires)
- The crystal, interacting with the beam, reduces the particle density on the extracted separatrix in very well defined transverse region
- The depleted region is then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



Angular spread at the SPS

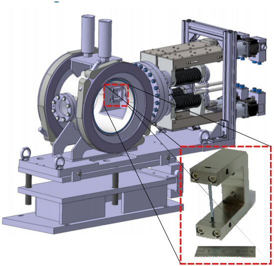
- The crystal CH angular acceptance (RMS), from measurements, is $\sigma_{\theta,CH} = 5.4\,\mu\text{rad} \approx \theta_c/2 = \sqrt{2U_{max}/pv}/2$
- As the CH angular acceptance is essentially the critical angle, and this goes as $1/\sqrt{p}$, it is tiny for the SPS...
- As previously shown, the angular spread was reduced of about 20% using **COSE** $\Rightarrow$ 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)

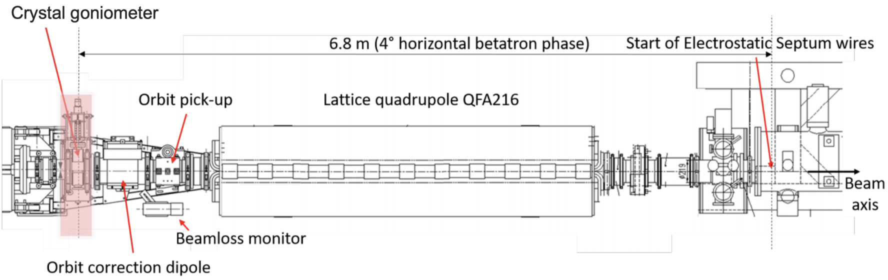




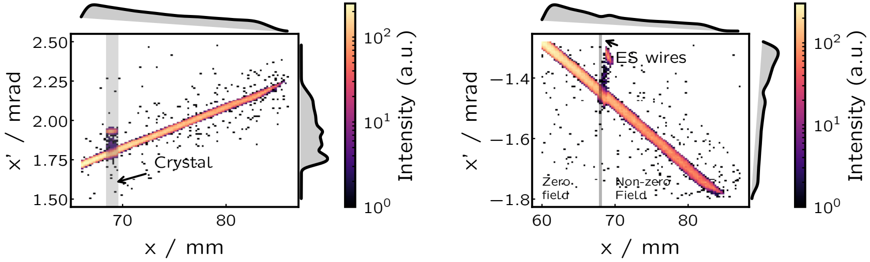
Local shadowing of the SPS-ZS

- 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 + *pycollimate*. There was the need to speed up element by element tracking simulations to perform the scans that will follow (more details in tomorrow's talk)
- 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 reduces measurements, see later for details)

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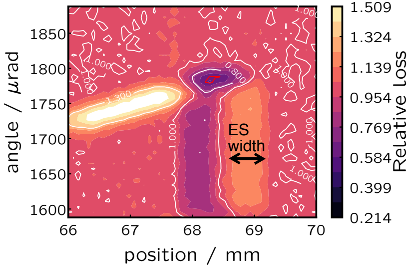

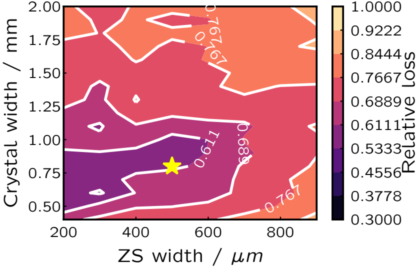

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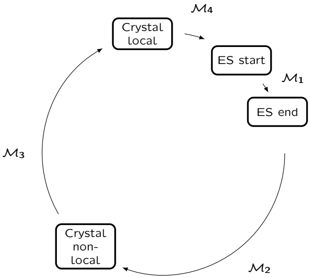
Non-local shadowing of the SPS-ZS

- 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 ⇒ negative bump hence no interference with fast extraction elements of LSS4
  - 2 extraction sextupoles between the crystal and the ES ⇒ large gain for angle to position transformation, this is key to reach the factor 4 reduction!
  - Negative CH kick (towards the inside of the ring) also significantly contributes to the factor 4 reduction observed in simulations



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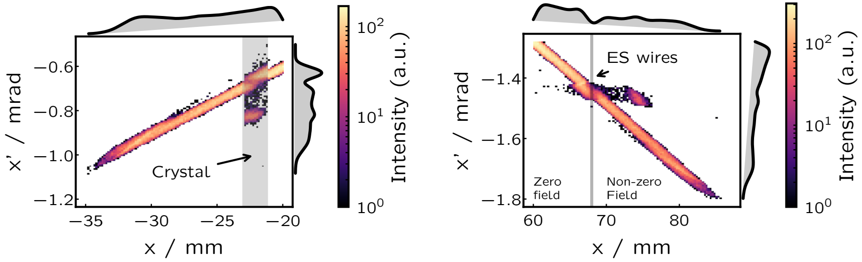

- The relative phase-advance between crystal and ES, in this case upstream of QFA.418, is about $n \times 180 + 12°$ (where n is odd)
- This is basically the same as the local case, but thanks to the strong extraction sextupoles between crystal and ES the gain in position is much larger than what predicted from linear transformation
- This gives smaller emittance for the extracted beam $\Rightarrow$ investigation ongoing to see if this can be optimised even further

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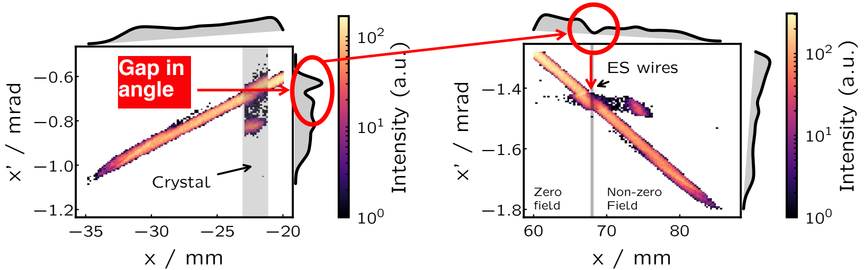

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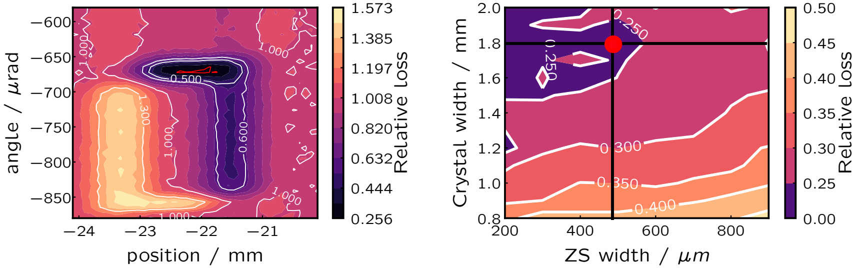

- A max reduction of about 75 % is achieved by placing a 1.8 mm thick crystal in LSS4 close to the QFA.418 ($s = 4031$ m)
- Up to a ZS thickness of about 500 μm, a 1.8 mm thick crystal is needed to guarantee the factor 4 reduction...

Local Shadowing

- Maximum possible loss reduction using single crystal in CH ⇒ 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

- Maximum possible loss reduction using single crystal in CH ⇒ 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
- Thicker crystal (1.8 mm) than for local case, hence almost double of local activation expected (although still very low!)

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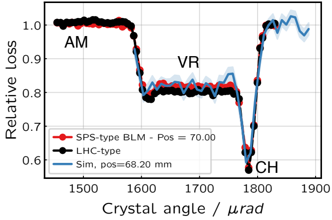

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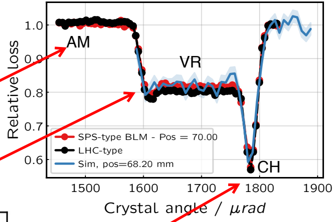

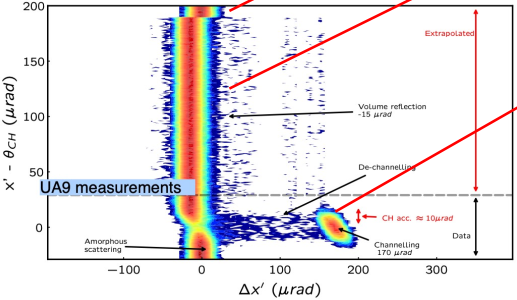

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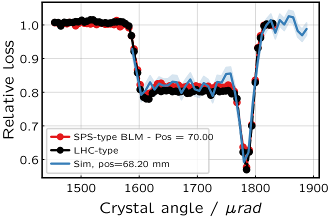
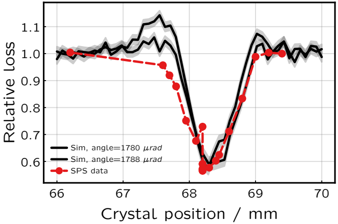
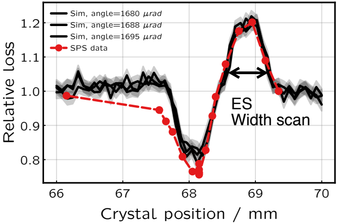
- Linear scans in VR and CH were also performed (or reconstructed from angular scans) ⇒ the loss increase is de facto a fine scan of the ES effective width!







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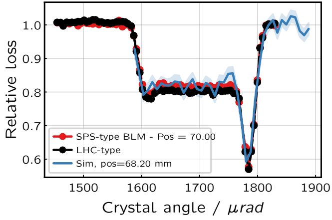

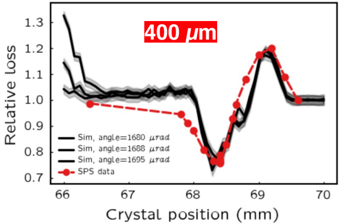

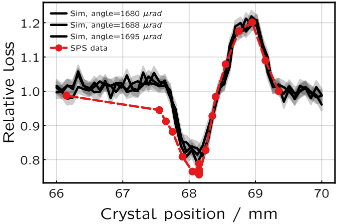

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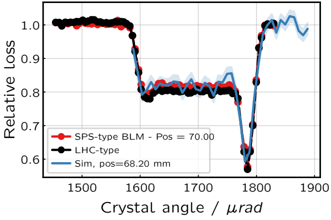
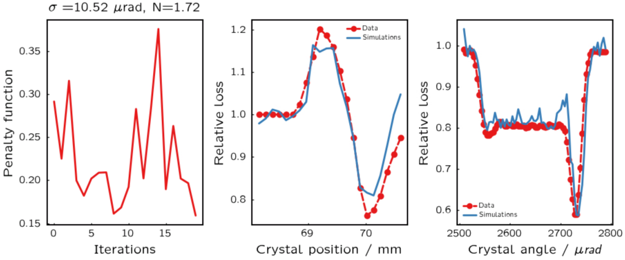
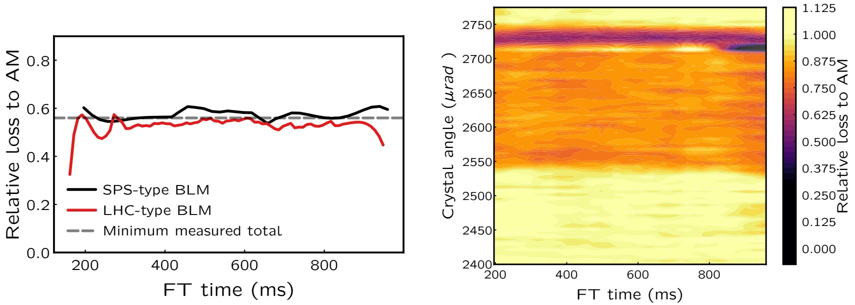




Loss reduction along the extraction

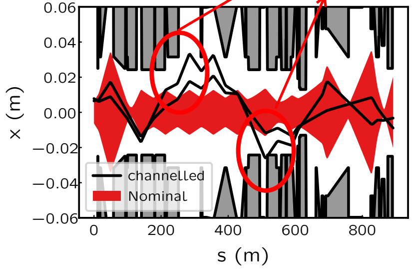
- We also measured loss reduction as a function of time (during spill essentially)...
- Here we can see a very constant loss reduction all along the spill...proving the effectiveness of the separatrix control methodology (see Verena's talk for the actual comparison)!

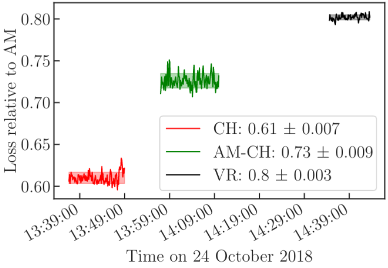


Stability and transport in the line

- 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^{11} p

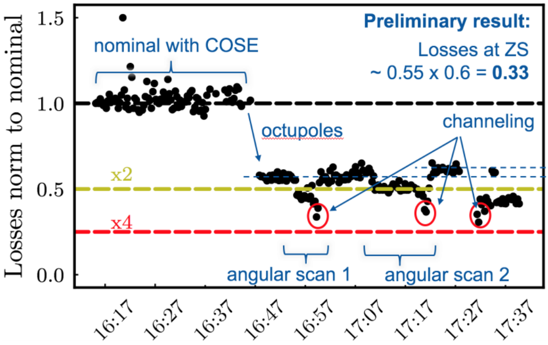
Local bumps needed to avoid losses





Crystal + octupoles: very preliminary

- Very quickly, and on the last MD of the year, we managed to combine 2 loss reduction methodologies: crystal shadowing + separatrix folding (see Matthew's talk on SPS slow extraction with octupoles)
- 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!



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)
- Simulations for **non-local version of crystal shadowing proposed and possible 75% loss reduction predicted** (assuming same ES width...)
- Operational deployment of local shadowing foreseen at restart in 2021
- Work ongoing to try to test non-local shadowing during next run
- Further optimisation of loss reduction via crystal shadowing might be achievable using multiple crystals in VR - work ongoing to quantify that
- **Loss reduction target of x4 for SPS slow extraction for future operation seems in reach!**

Thank you!

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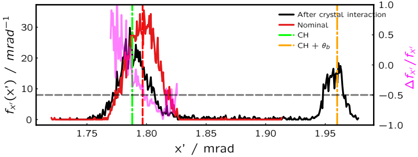
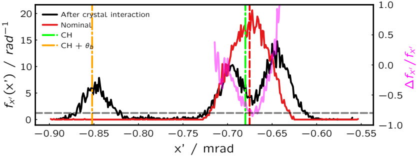
Backup

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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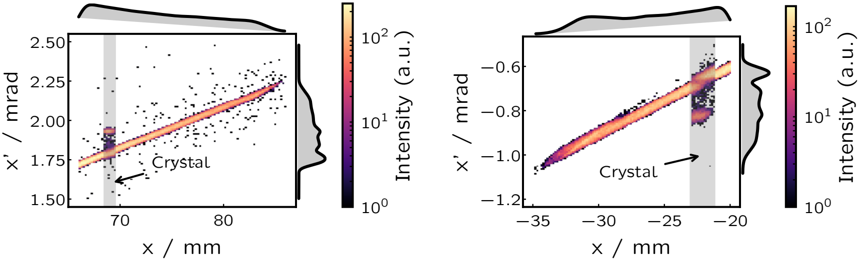
- We saw what it can be the maximum density reduction only looking at the angular distributions at the crystal $\Rightarrow$ this of course needs to be translated into position!



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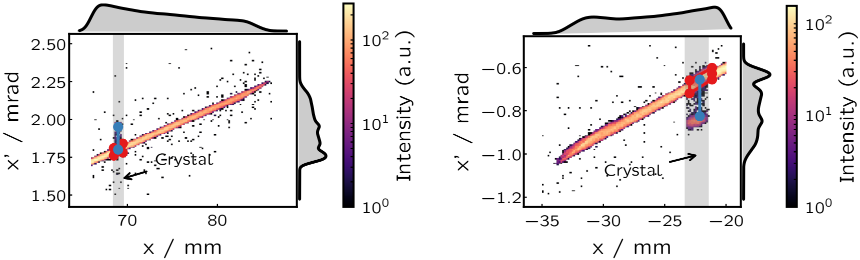

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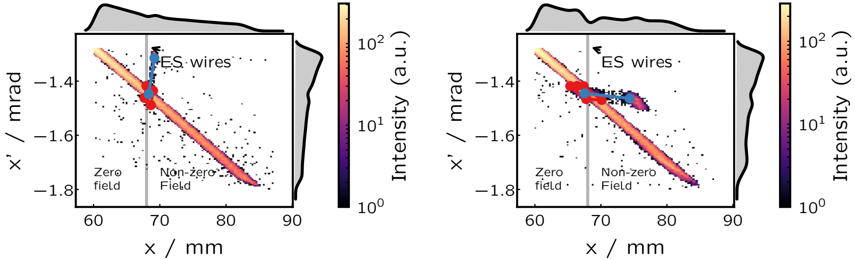

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- To do this, we can look at a simple model only considering the part of the separatrix interacting with the crystal and then track it to the ZS
- Then comparing with a simple linear rotation from crystal to ZS, it is clear how **the non-local location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