

Demonstration of loss reduction using a thin bent crystal to shadow an electrostatic septum during resonant slow extraction

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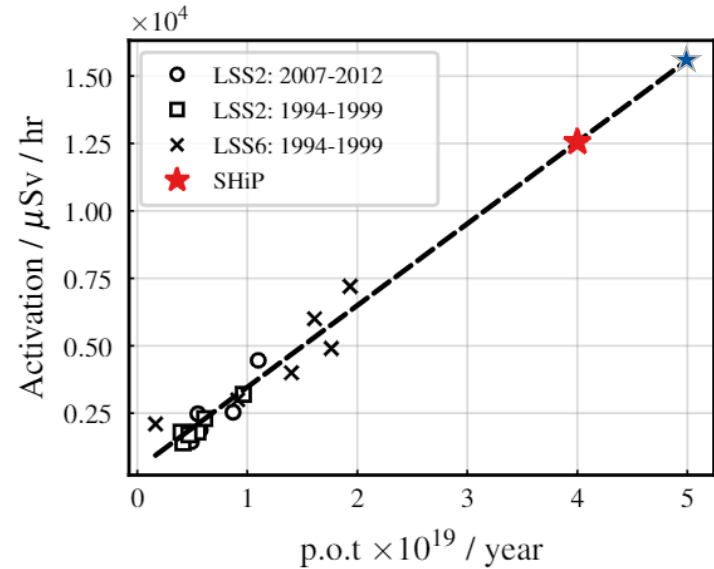
Thanks go to the UA9 Collaboration and the PBC study

Outline

- Motivation and 400 GeV SPS slow extraction
- Septum shadowing concept with bent crystal
- Simulation results
- Crystal characteristics and prototype goniometer installation
- Experimental results
- Outlook

Motivation

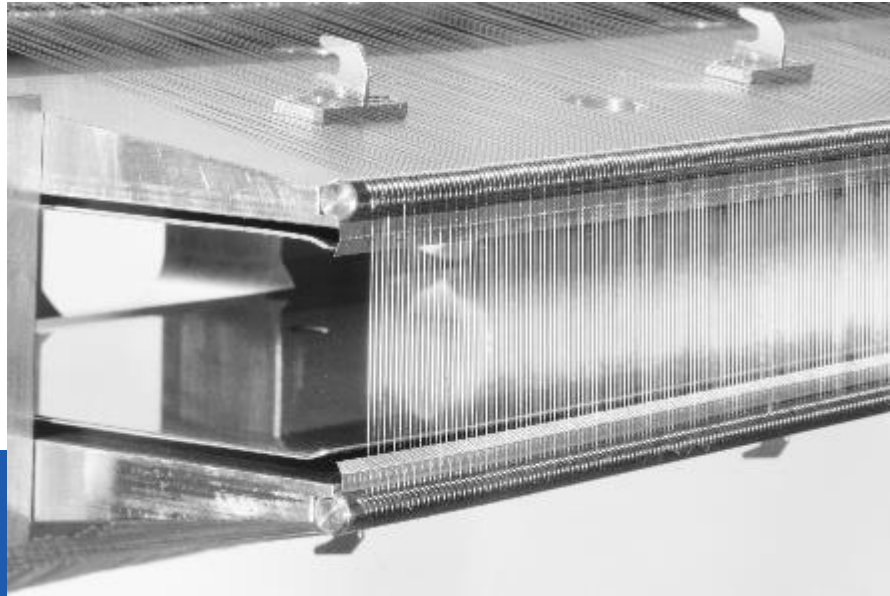
- Proposals for new ‘hidden-sector’ Fixed Target experiments at CERN rely on big SPS performance improvement
- SHiP needs 4×10^{19} PoT/y, 350 kW beam power: similar to CNGS but with slow extraction
- Present 400 GeV slow extraction of 1.3×10^{19} PoT/y limited by extraction beam loss and activation
- We are studying methods of reducing slow extraction beam loss, aiming at **x4** improvement



SPS Slow extraction and losses

WEPMP031
WEPMP024

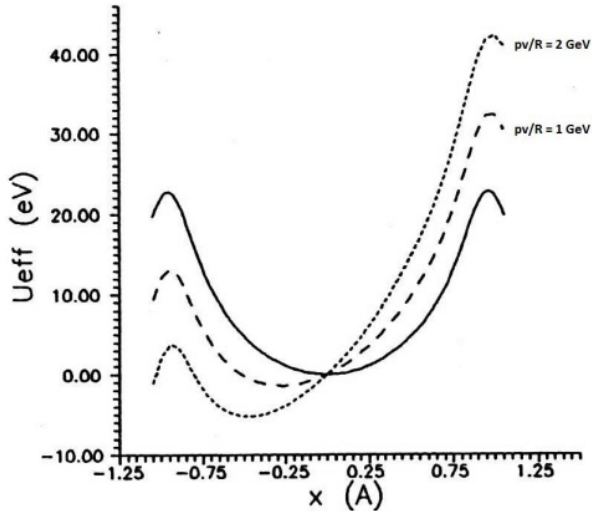
- Extract 400 GeV protons over ~seconds with 3rd integer resonance
- Thin electrostatic wire septum: 16 m long, 11k 60-100 μ m W/Re wires
- Present operational losses from scattering on ES wires 3.4%
(determined by spiral step, separatrix angular width and ES width)



Bent Si crystals for guiding particle beams

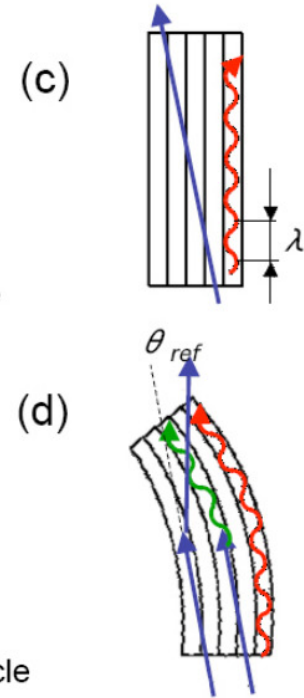
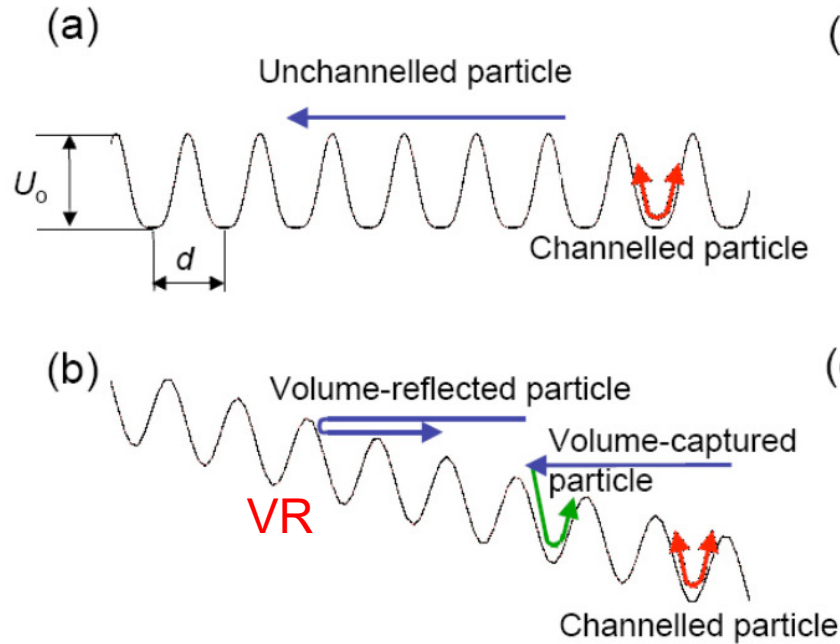
- A single 2 mm long, 0.8 mm wide crystal deflects 400 GeV protons by 170 μ rad - would need a \sim 120 T magnetic field

Crystal inter-nuclear potential



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

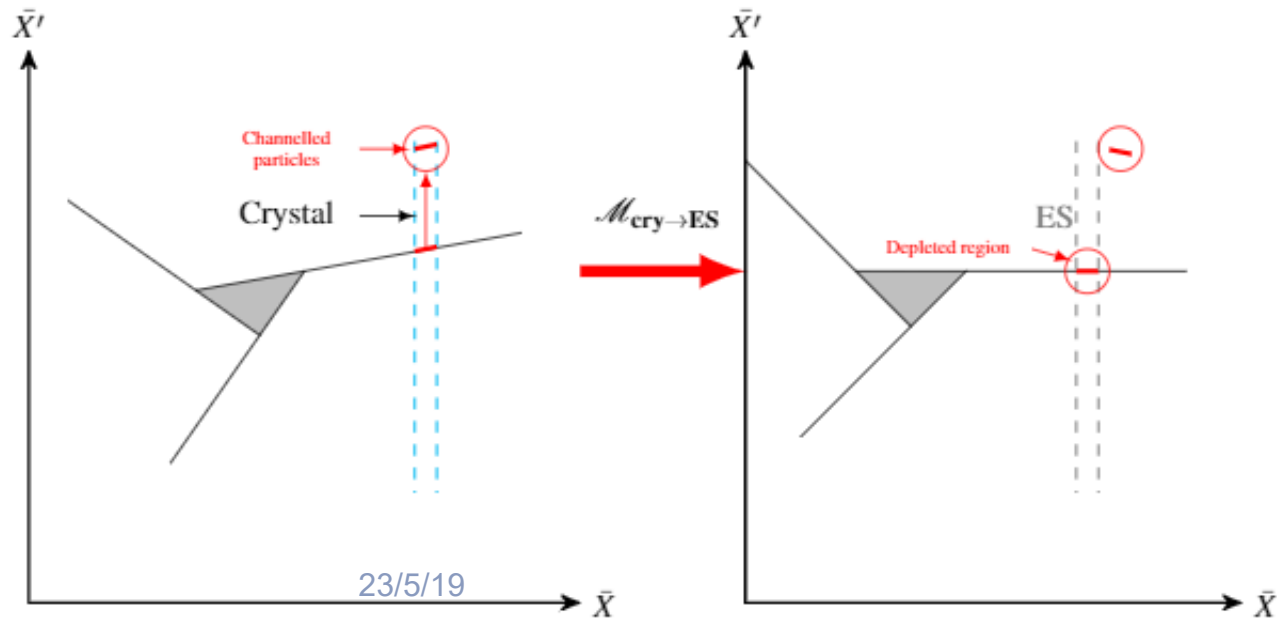
Critical angle
for channeling



W.Scandale

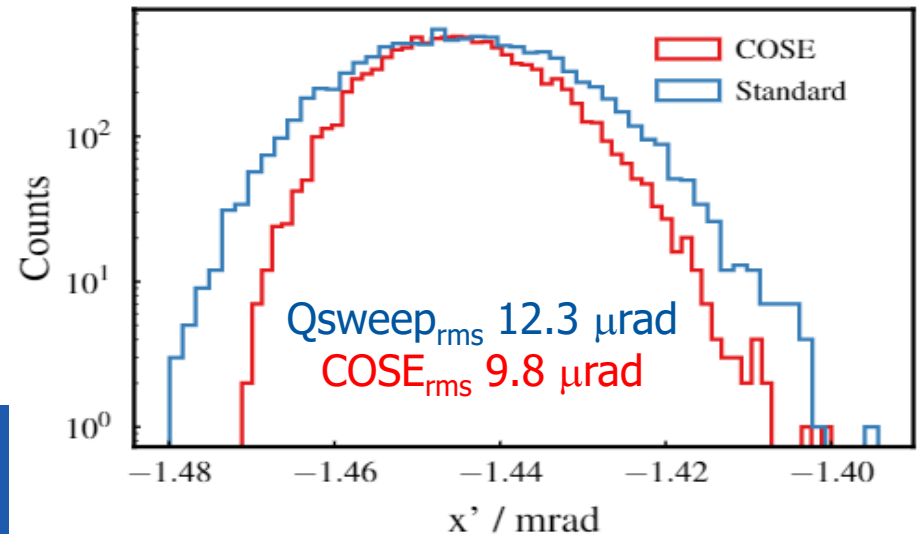
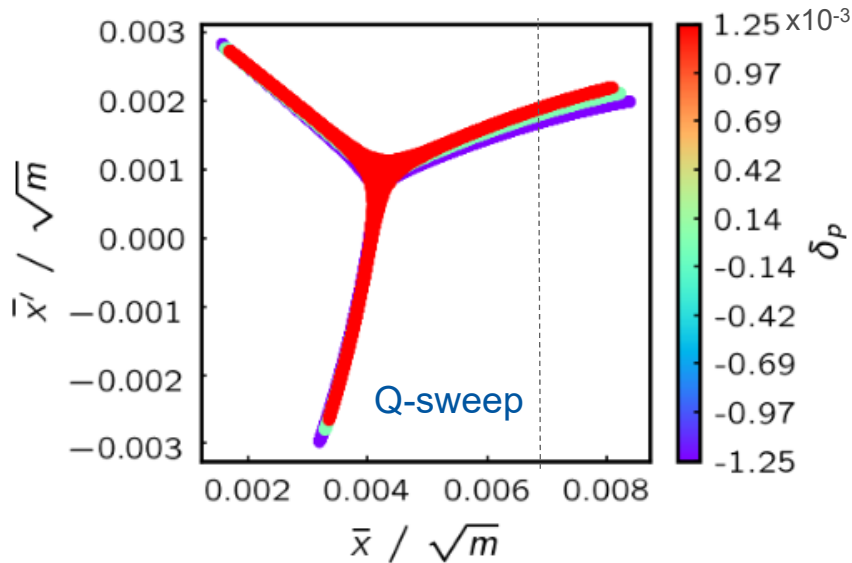
Crystal shadowing: concept

- A thin bent crystal is positioned upstream of ES
- Crystal aligned in channelling or VR, locally depletes separatrix density
- Depleted region aligned to ES wires to reduce losses



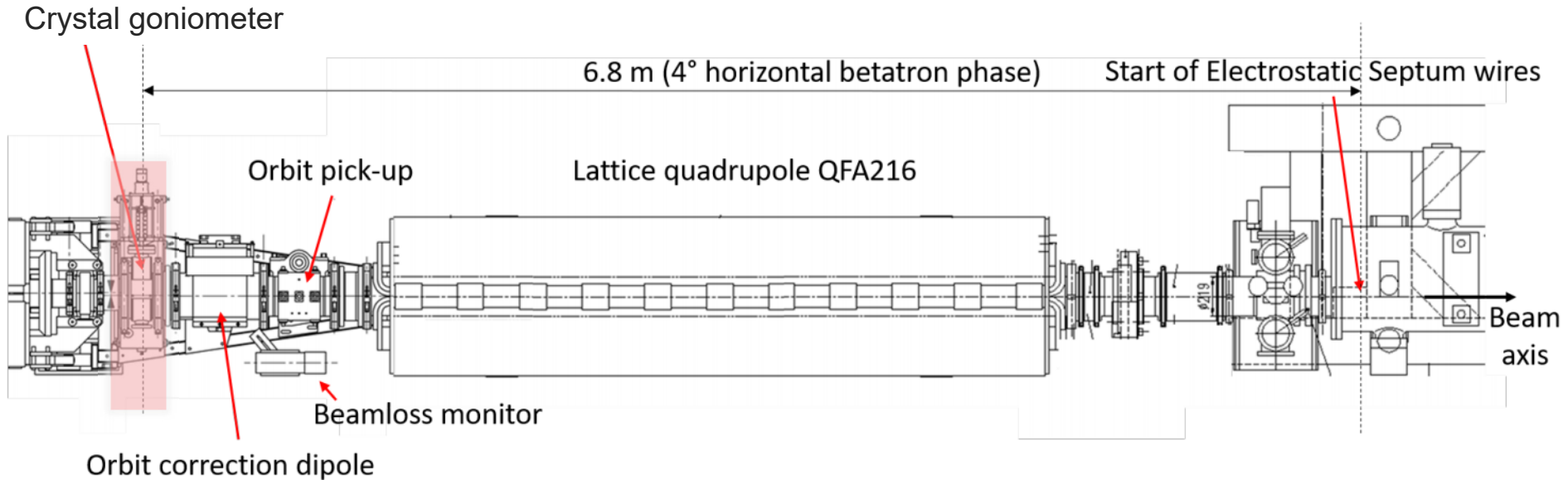
Angular acceptance

- Crystal channelling angular acceptance is $5.4 \mu\text{rad}$ (1σ rms)
- Extraction with Q-sweep and large $\delta p/p$ gives separatrix rotation in spill
- With Q_sweep separatrix angular width $12.3 \mu\text{rad}$ (1σ). New 'COSE' extraction in SPS reduced this to $9.8 \mu\text{rad}$



SPS deployment

- Location ~ 7 m (4°) upstream ES available, inside extraction bump
- Compact goniometer required : **187 mm** total longitudinal space

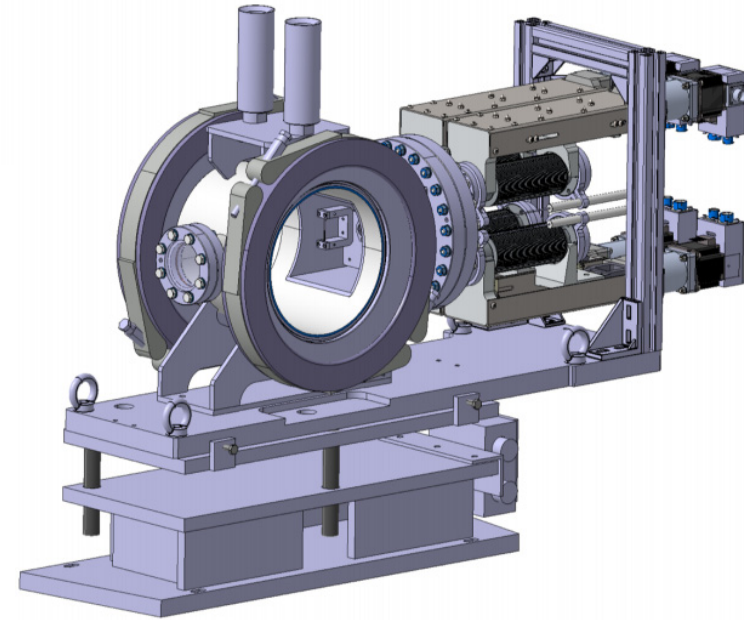
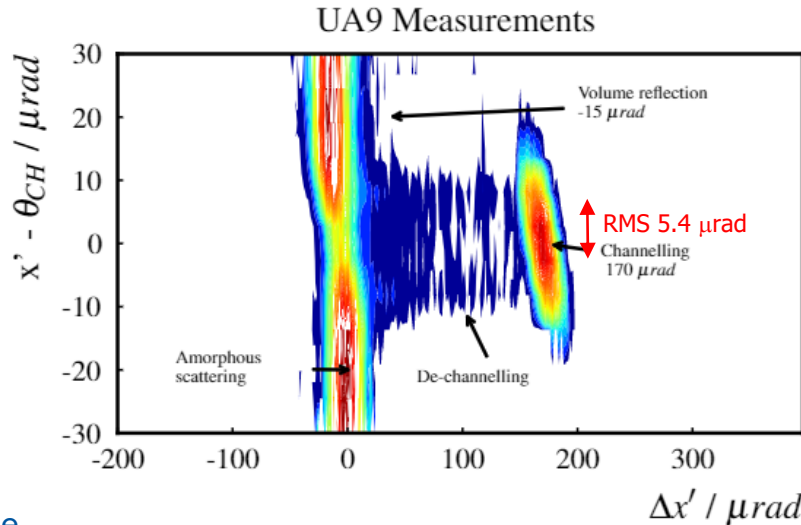


Prototype goniometer and crystal

- Compact goniometer developed with UA9
- Crystal characterised in H8 (180 GeV π^+)



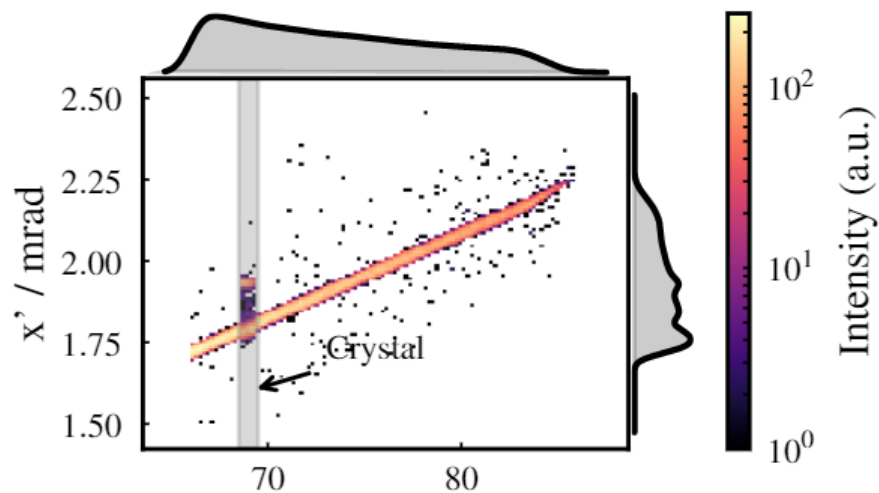
Si crystal is 0.8 mm wide,
2 mm long, 35 mm high



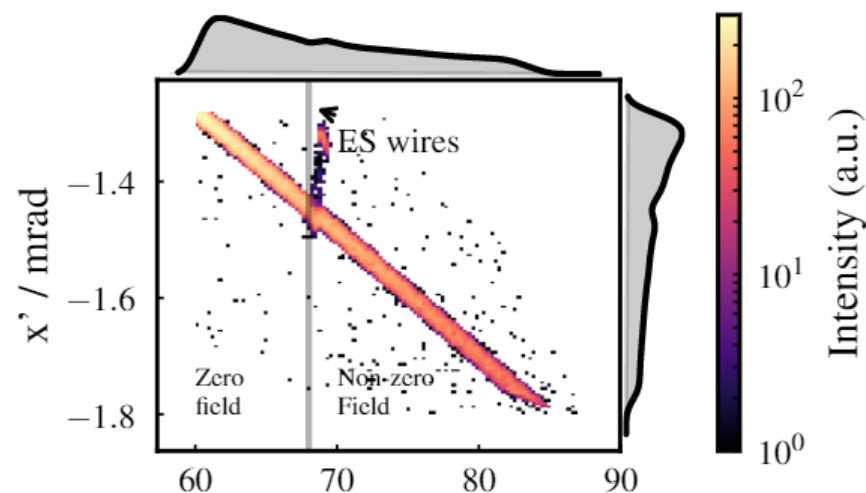
187 mm total length

Tracking simulations of performance

- Full extraction dynamics modelled using madx + pycollimate
- Parametric optimization made with 4th order PTC maps + pycollimate



Separatrix presentation at crystal

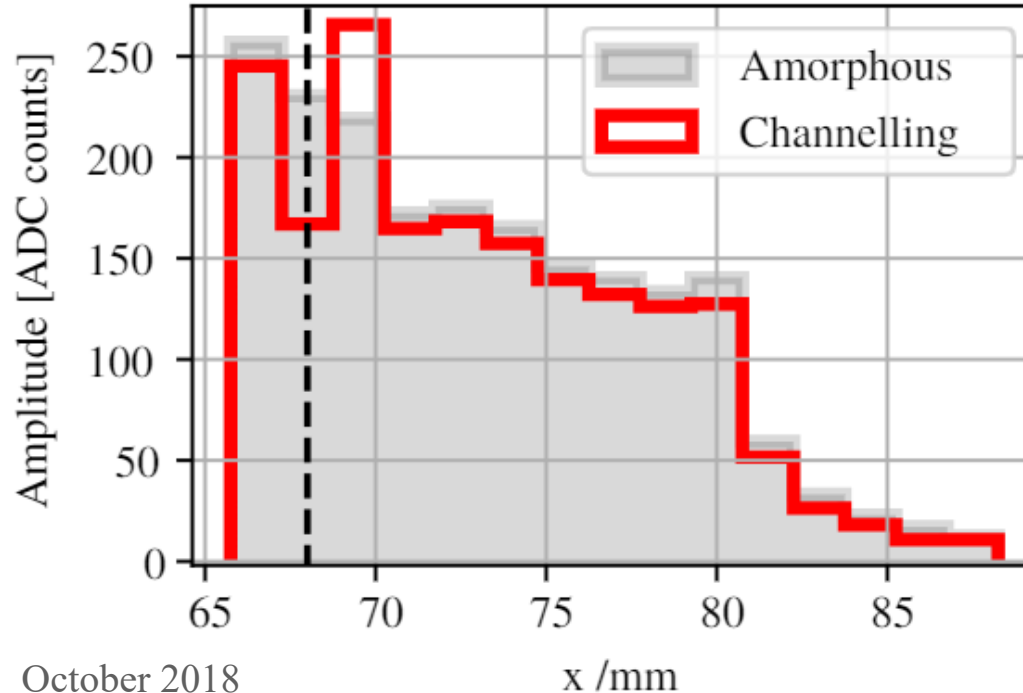


Separatrix presentation at ES entry

Experimental results

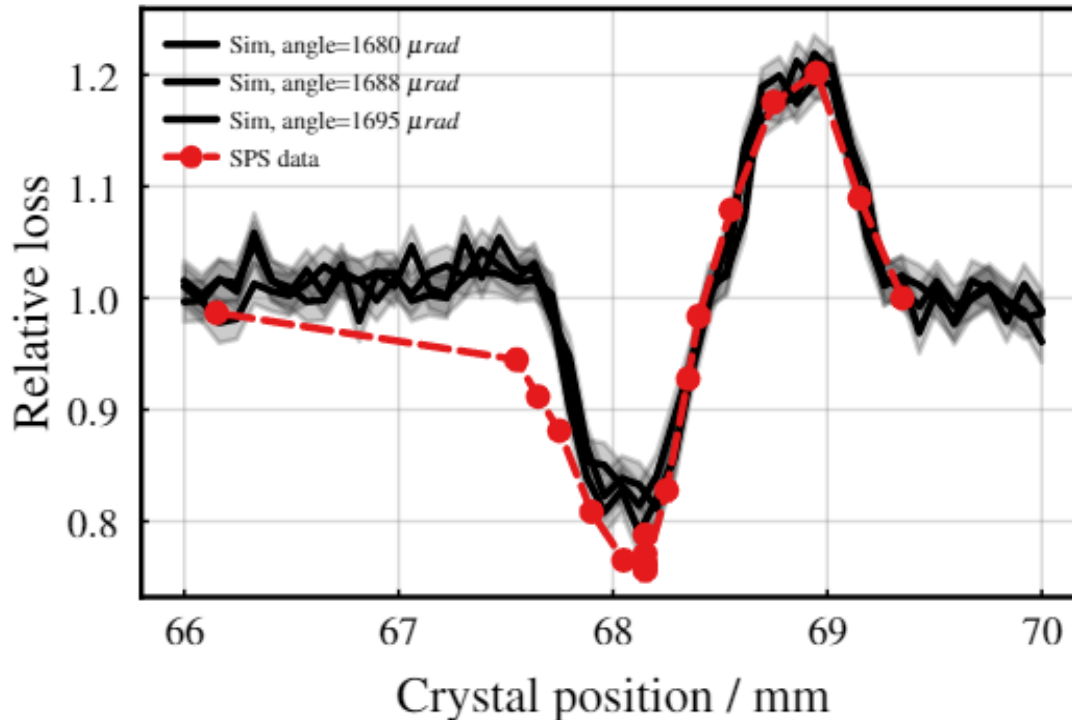
- Measurements on 400 GeV, 1s spill used for SHiP tests, 5×10^{12} p/spill
- SEM grid profile upstream ES shows density reduction in channelling

Dip in extracted
separatrix profile, with
SEM bin resolution
1.5 mm



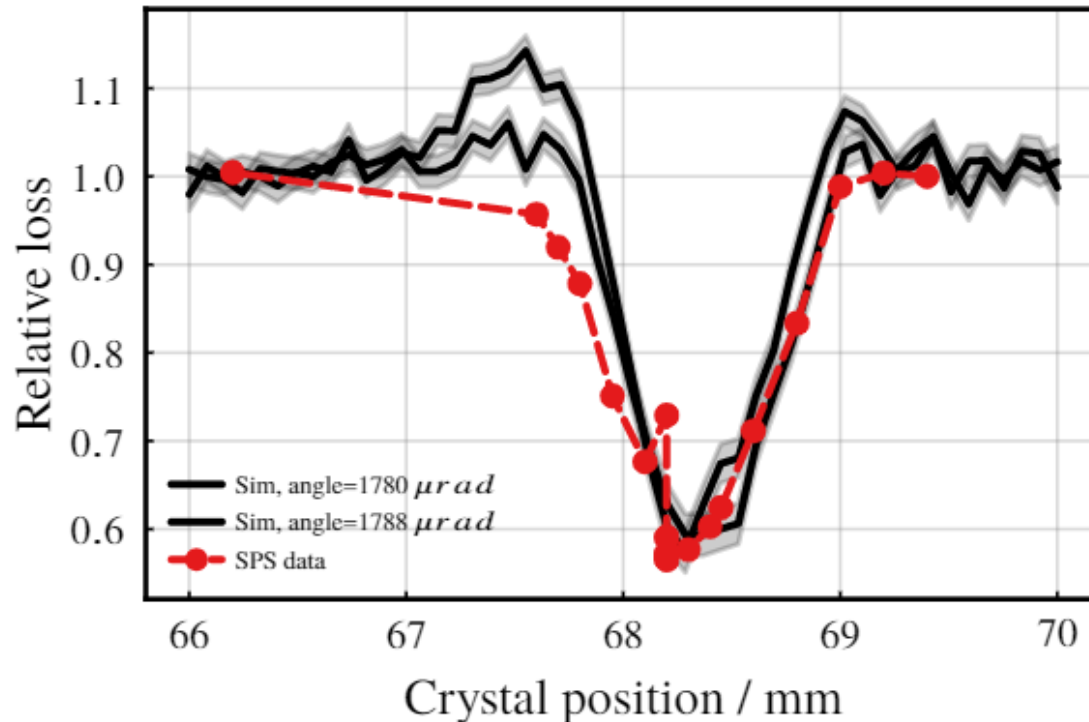
Experimental results: VR

- Linear scan of crystal position in VR ($-15 \mu\text{rad}$ deflection): 20% gain
- $500 \mu\text{m}$ ES width fitted from shape (narrow beamlet is scanned across ES)



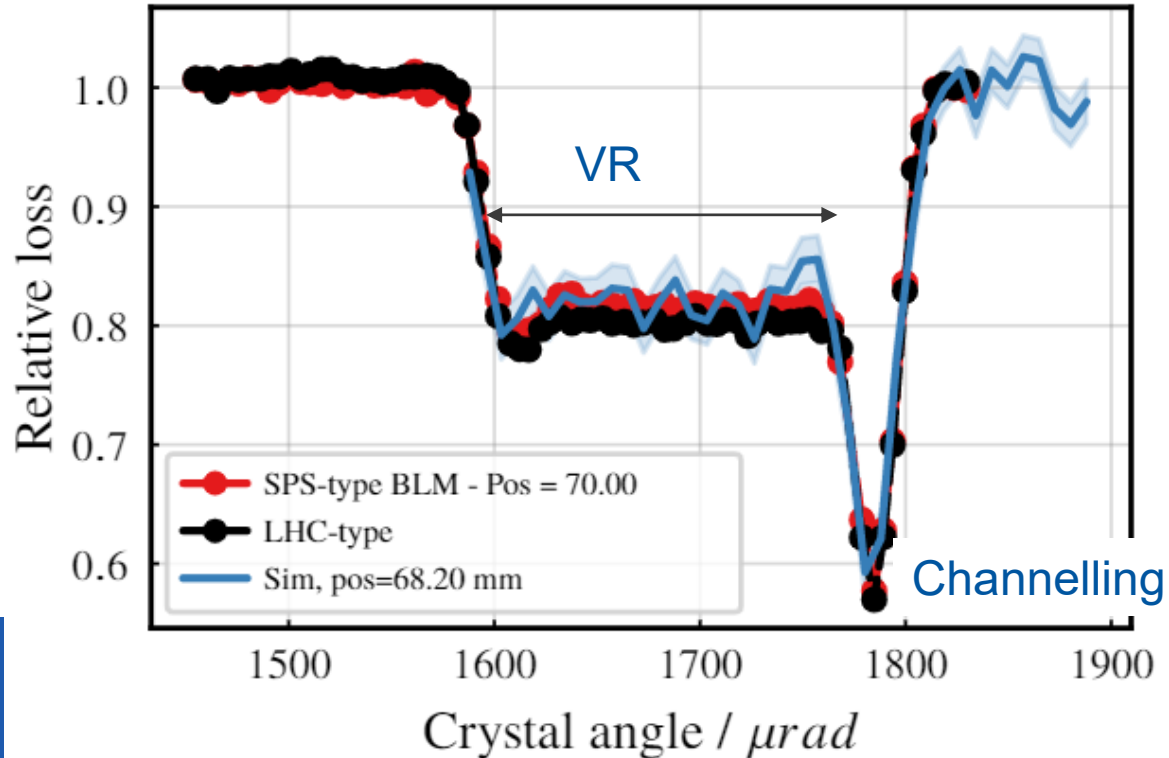
Experimental results: channelling

- Crystal position scanned while in channelling, loss reduction profile agrees with simulations, in best case reaches 44%



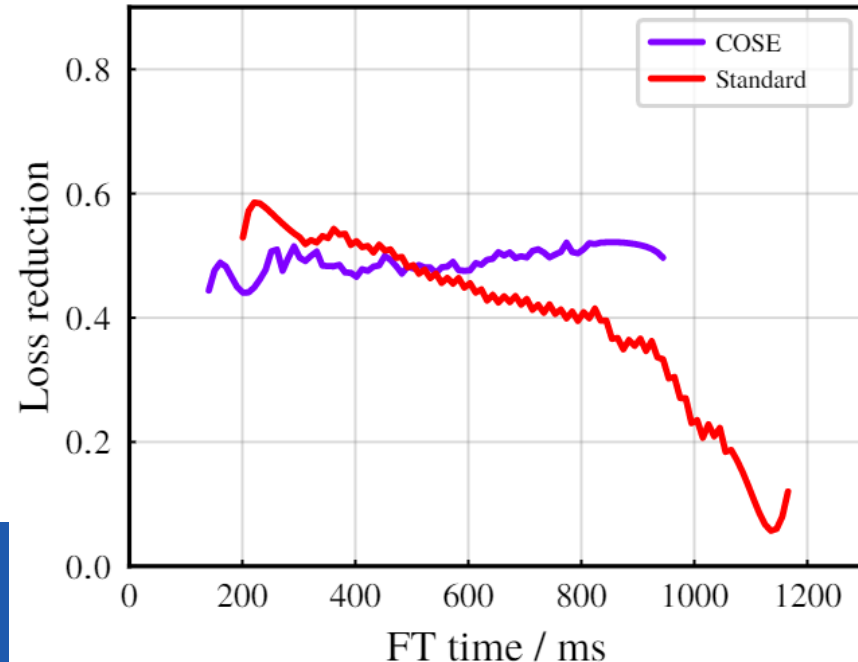
Experimental results: angular scan

- Crystal angle scanned while at optimum X position, reproduce simulations for both volume-reflection and channelling features



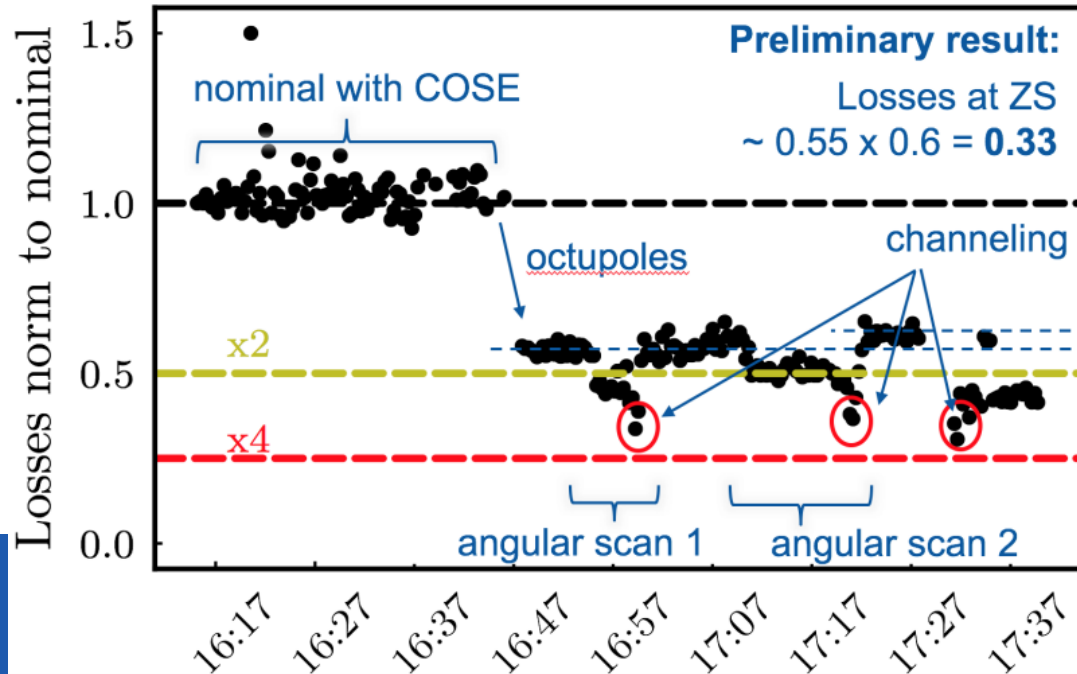
Experimental results: time resolved losses

- Measured time-resolved losses through spill with standard Q-sweep and Constant-Optics (COSE) extraction
- Separatrix changes with Q-sweep (rotation + instantaneous width?), while stable with COSE



Experimental results: crystal + octupoles

- Method to reduce losses using octupoles to distort separatrix distribution at ES was tried in combination with crystal shadowing
- Loss reduction of factor 3.1 observed on initial (and only) attempt

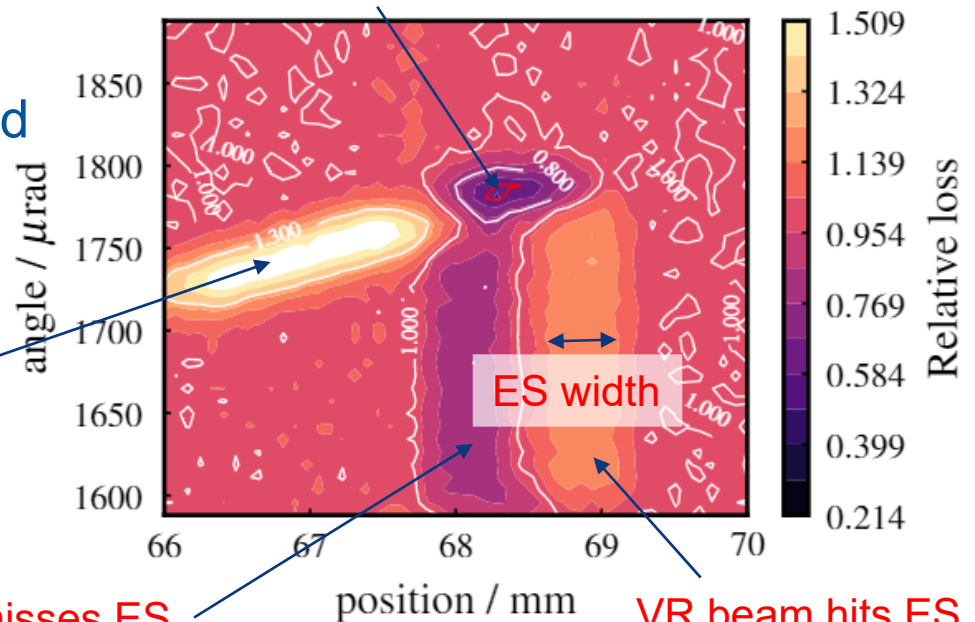


Simulation of full parametric scan

- Losses simulated as function of aligned crystal position and angle
- Used 'measured' ES width
- Crystal 0.8 mm wide, 172 μrad
- Best loss reduction 44%
- Optimizer input?

Channelled beam hits ES

Channelled beam extracted



Other experimental observations

- Stability in both channelling and VR over several hundred cycles was measured, with no change of efficiency
- Operation with high intensity ($2.8e13$) was tested (in VR only), for 13 hours, with no outgassing or loss of efficiency
- Setup time for optimising position and angle was fast, within a few SPS supercycles (few minutes)

Conclusion and Outlook

- Thin (0.8 mm), short (2 mm) bent Si crystal was successfully used to reduce 400 GeV slow extraction loss per proton by a factor of **1.8**
- Good agreement with simulation, with ES width of 500 μm
- Combined with octupole separatrix shaping: factor **3.1** loss reduction
- Operational deployment is planned for SPS restart in 2021, starting with just local crystal shadowing
- Further optimisation possible: factor 4 gain with crystal alone may be possible with non-local shadowing (but more complicated operation)
- Target of loss reduction of **factor 4** for SPS slow-extraction for future facilities seems possible

Additional references

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