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

Brennan Goddard, CERN

F.M.Velotti, P.Bestmann, M.Butcher, M.Calviani, M.Di Castro, M.Donze, L.S.Esposito, M.A.Fraser, S.S.Gilardoni, B.Goddard, V.Kain, J.Lendaro, A.Masi, D.Mirarchi, M.Pari, J.P.Prieto, S.Redaelli, R.Rossi, W.Scandale, P.Serrano Galvez, R.Seidenbinder, L.S.Stoel, C.Zamantzas, V.Zhovkovska (CERN, Geneva, Switzerland) F.M.Addesa, F.Iacoangeli (INFN, Roma,Italy), F.Galluccio (INFN-Napoli, Napoli), F.Murtas (INFN/LNF, Frascati, Italy), A.G.Afonin, Y.Chesnokov, A.A.Durum, V.A.Maisheev, Y.E.Sandomirskiy, A.Yanovich (NRC Kurchatov Institute - IHEP, Protvino, Russia) M.Garattini (CERN; Imperial College of Science and Technology, London), J.Borg, G.Hall, T.James, M.Pesaresi (Imperial College of Science and Technology, London), A.S.Denisov, Y.Gavrikov, Y.M.Ivanov, M.A.Koznov, L.G.Malyarenko, V.Skorobogatov (NRC “Kurchatov Institute” - PNPI, Gatchina, Russia)

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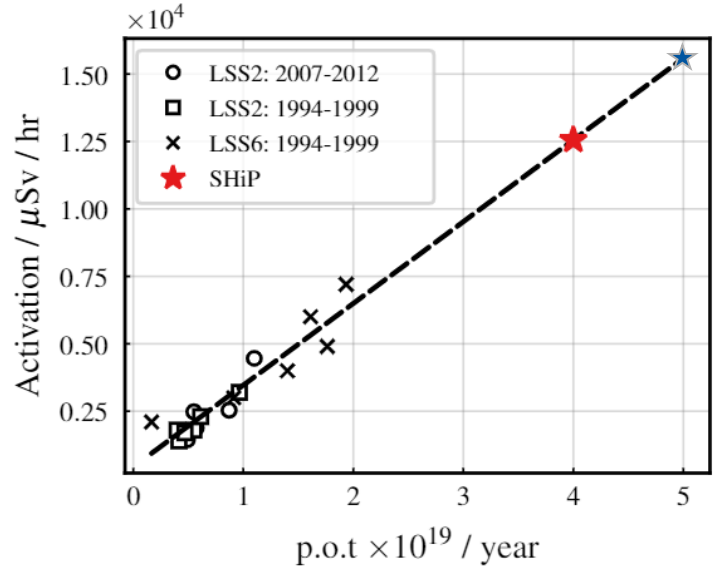
Outline

- 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

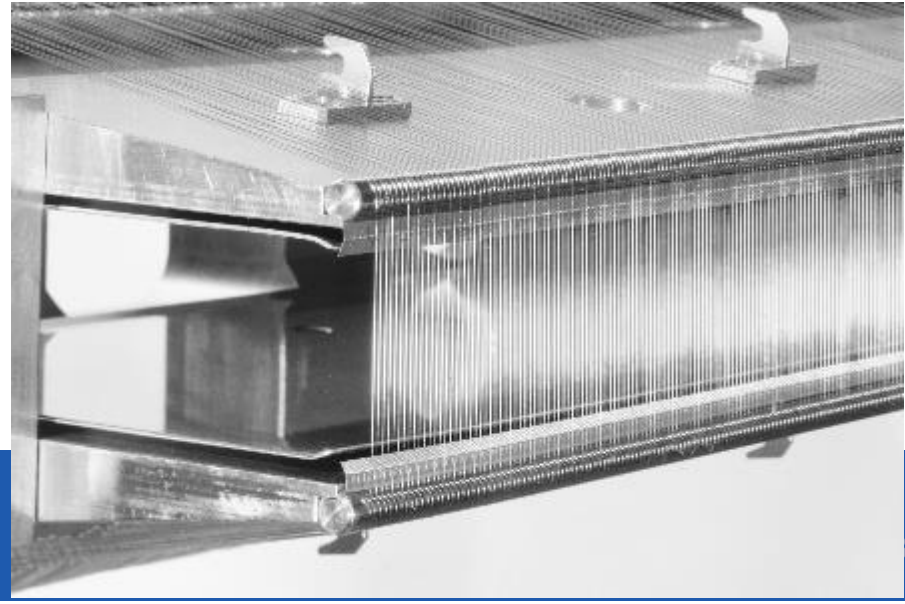
- Proposals for new ‘hidden-sector’ Fixed Target experiments at CERN rely on big SPS performance improvement
- SHiP needs 4x10^{19} PoT/y, 350 kW beam power: similar to CNGS but with slow extraction
- Present 400 GeV slow extraction of 1.3x10^{19} PoT/y limited by extraction beam loss and activation
- We are studying methods of reducing slow extraction beam loss, aiming at x4 improvement



SPS Slow extraction and losses

WEPMP031
WEPMP024

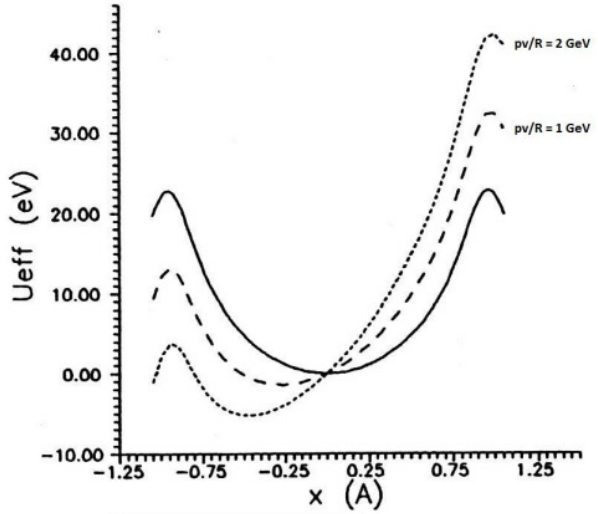
- Extract 400 GeV protons over ~seconds with 3rd integer resonance
- Thin electrostatic wire septum: 16 m long, 11k 60-100μm W/Re wires
- Present operational losses from scattering on ES wires 3.4%
  (determined by spiral step, separatrix angular width and ES width)



Bent Si crystals for guiding particle beams

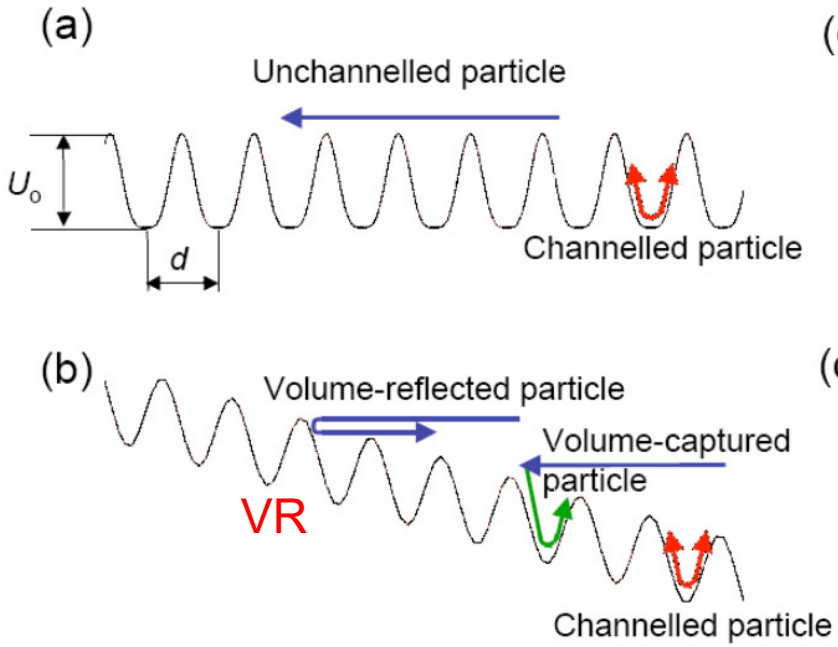
- A single 2 mm long, 0.8 mm wide crystal deflects 400 GeV protons by 170 μrad - would need a ~120 T magnetic field

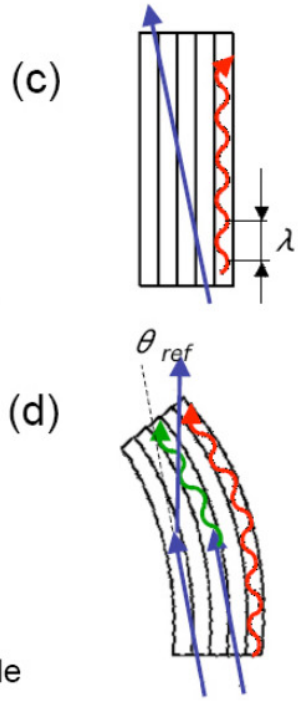
Crystal inter-nuclear potential



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

Critical angle for channeling

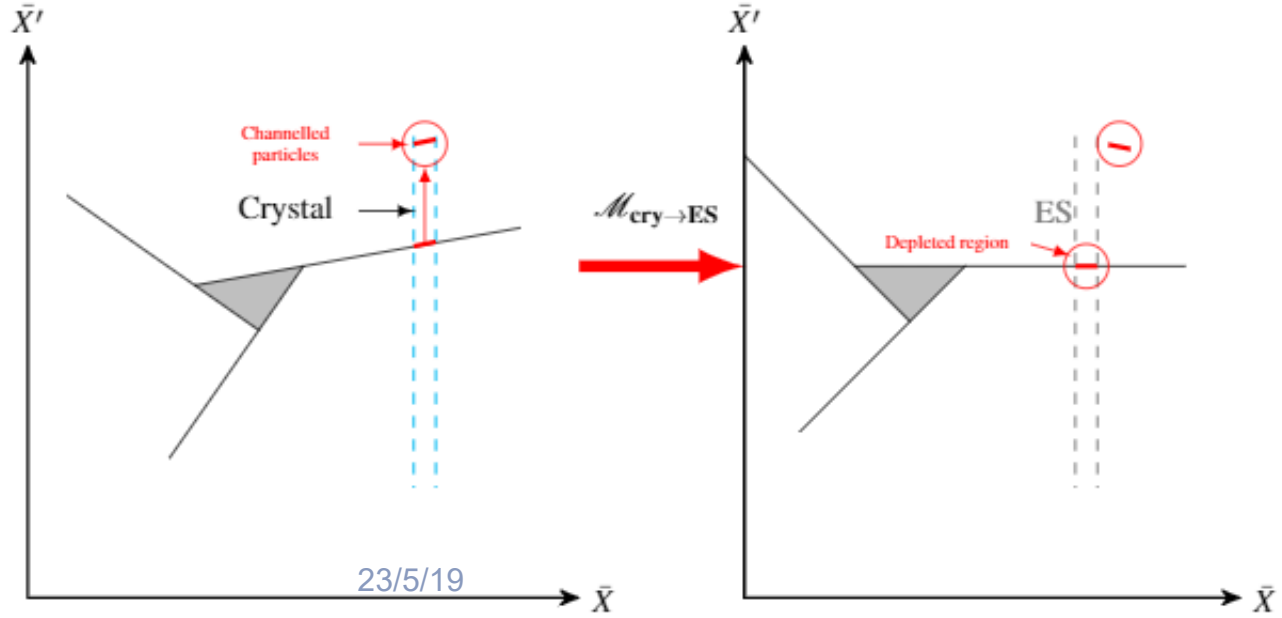




W.Scandale

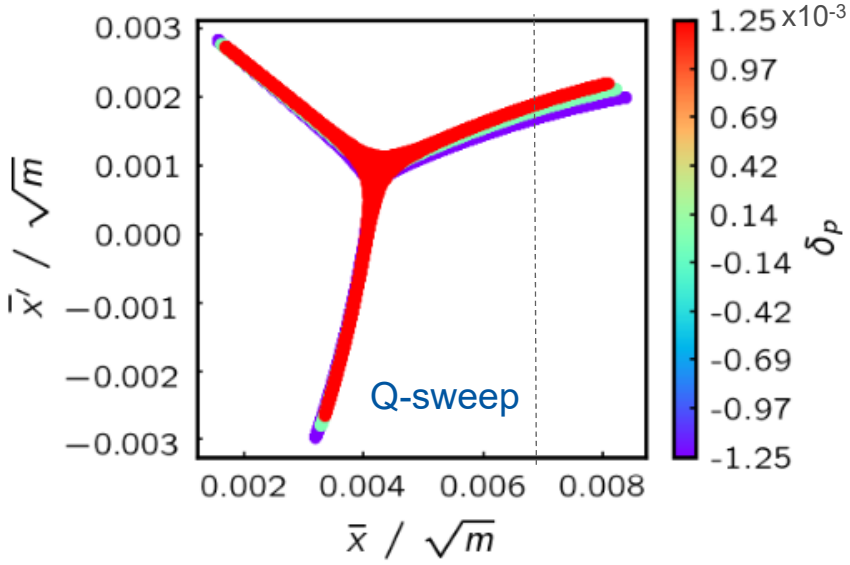
Crystal shadowing: concept

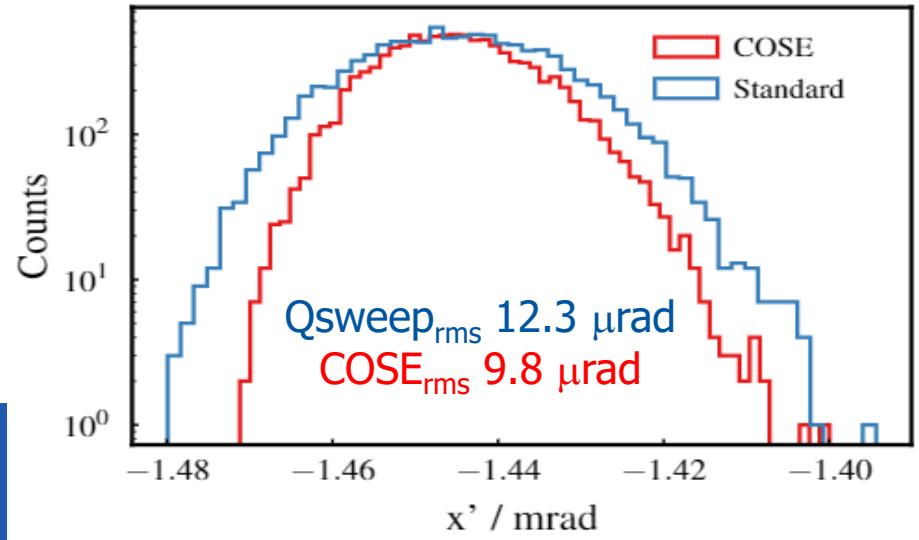
- A thin bent crystal is positioned upstream of ES
- Crystal aligned in channelling or VR, locally depletes separatrix density
- Depleted region aligned to ES wires to reduce losses



Angular acceptance

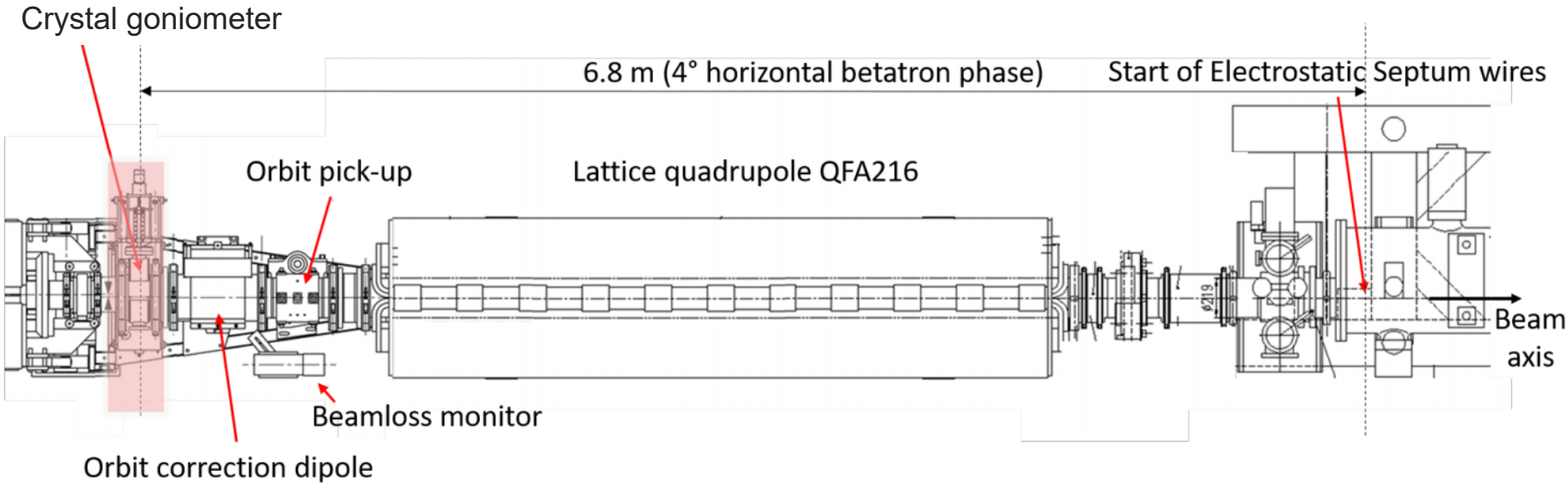
- Crystal channelling angular acceptance is 5.4 μrad (1σ rms)
- Extraction with Q-sweep and large δp/p gives separatrix rotation in spill
- With Q_sweep separatrix angular width 12.3 μrad (1σ). New 'COSE' extraction in SPS reduced this to 9.8 μrad





SPS deployment

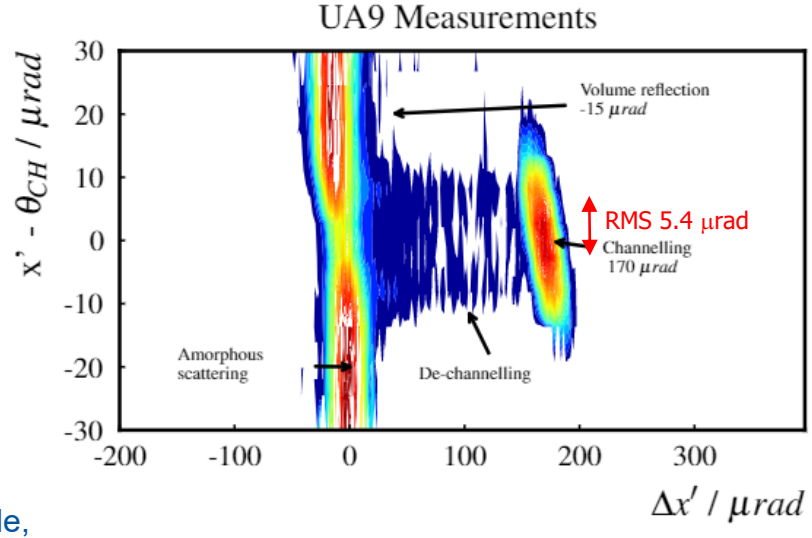
- Location ~7 m (4°) upstream ES available, inside extraction bump
- Compact goniometer required : 187 mm total longitudinal space

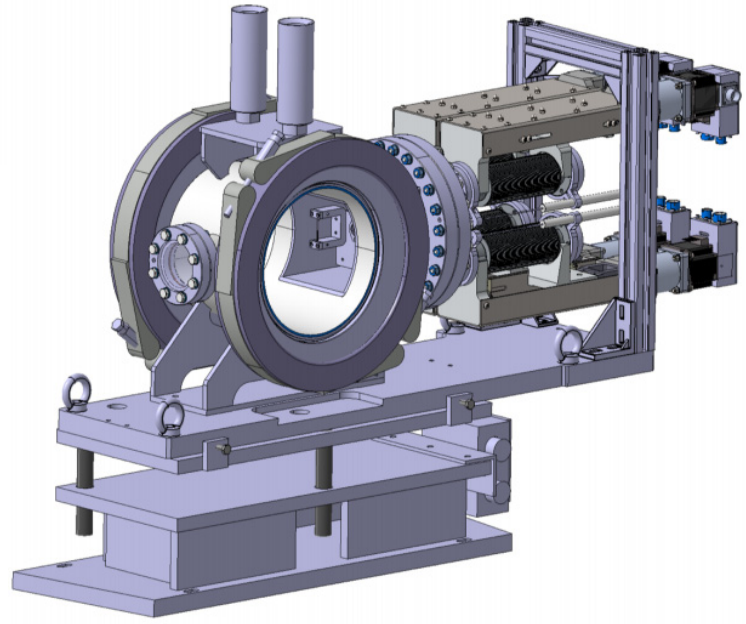


Prototype goniometer and crystal

- 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

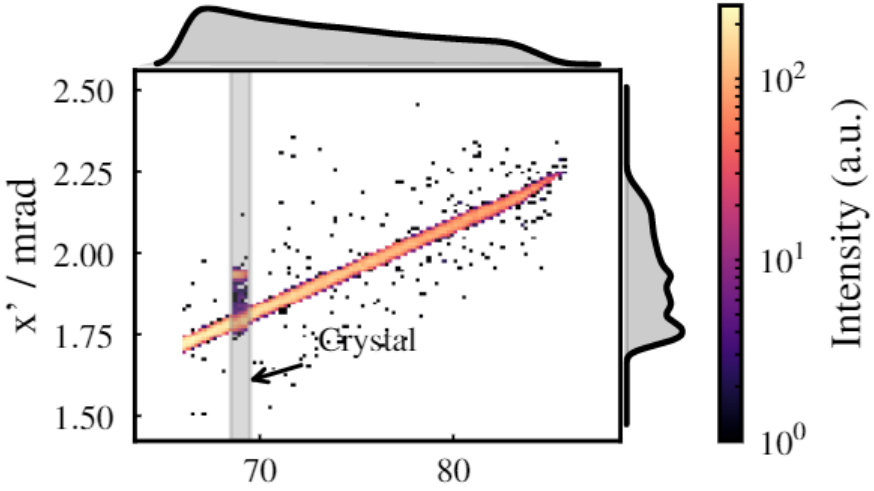




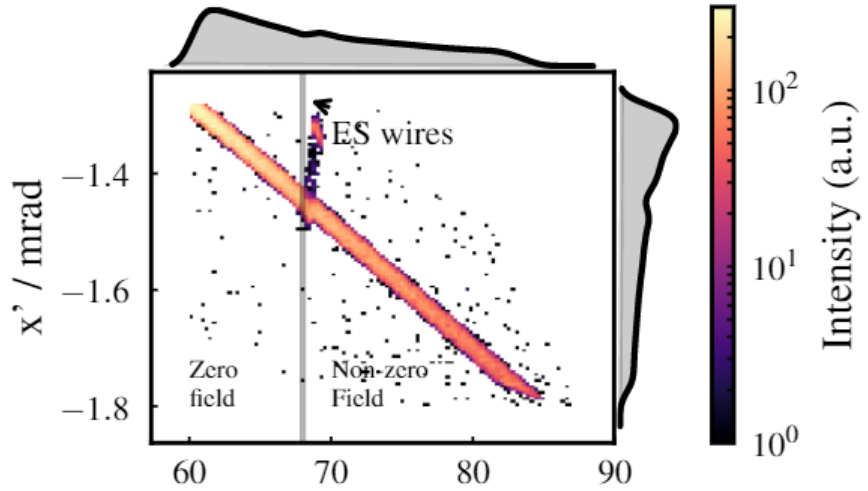
187 mm total length

Tracking simulations of performance

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



Separatrix presentation at crystal

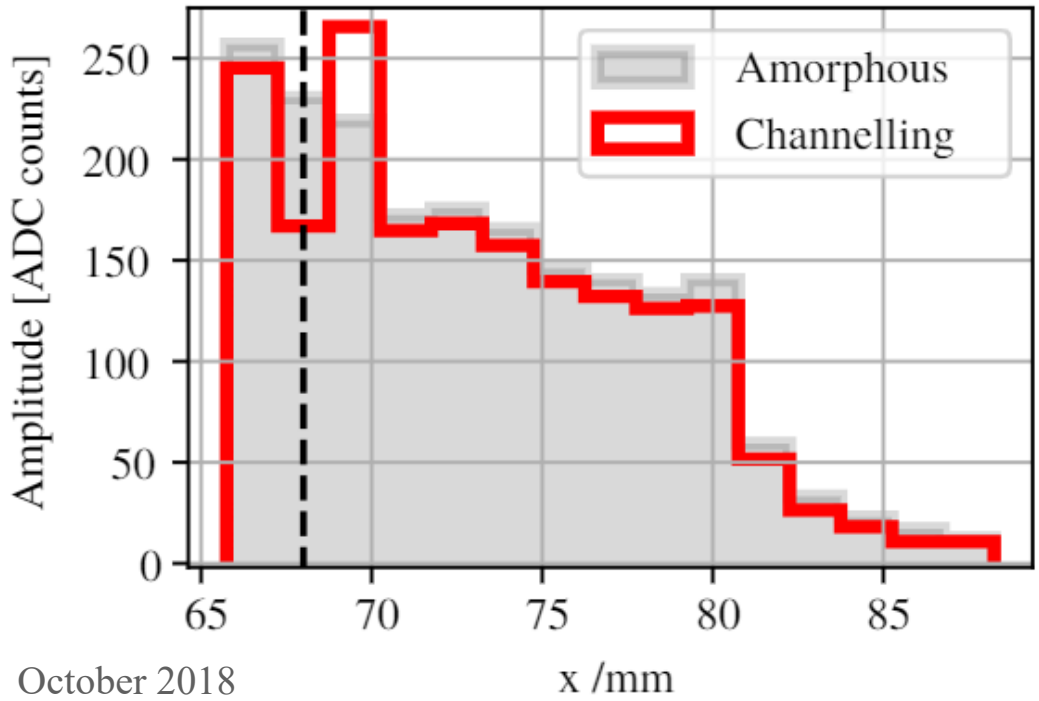


Separatrix presentation at ES entry

Experimental results

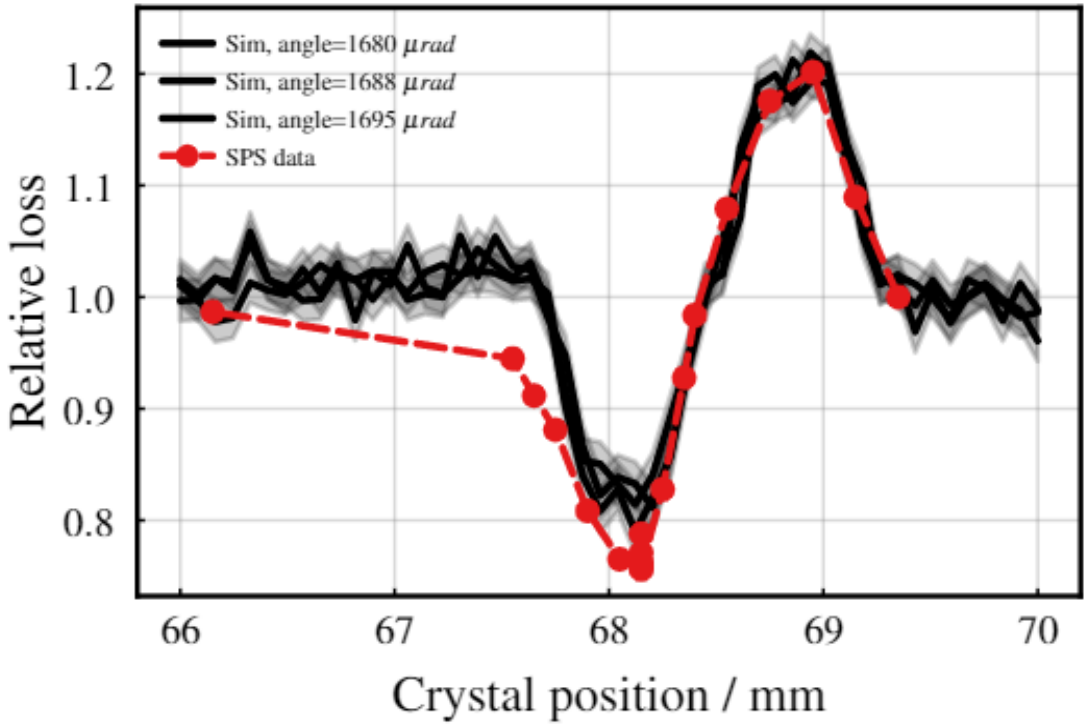
- Measurements on 400 GeV, 1s spill used for SHiP tests, $5x10^{12}$ p/spill
- SEM grid profile upstream ES shows density reduction in channelling

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



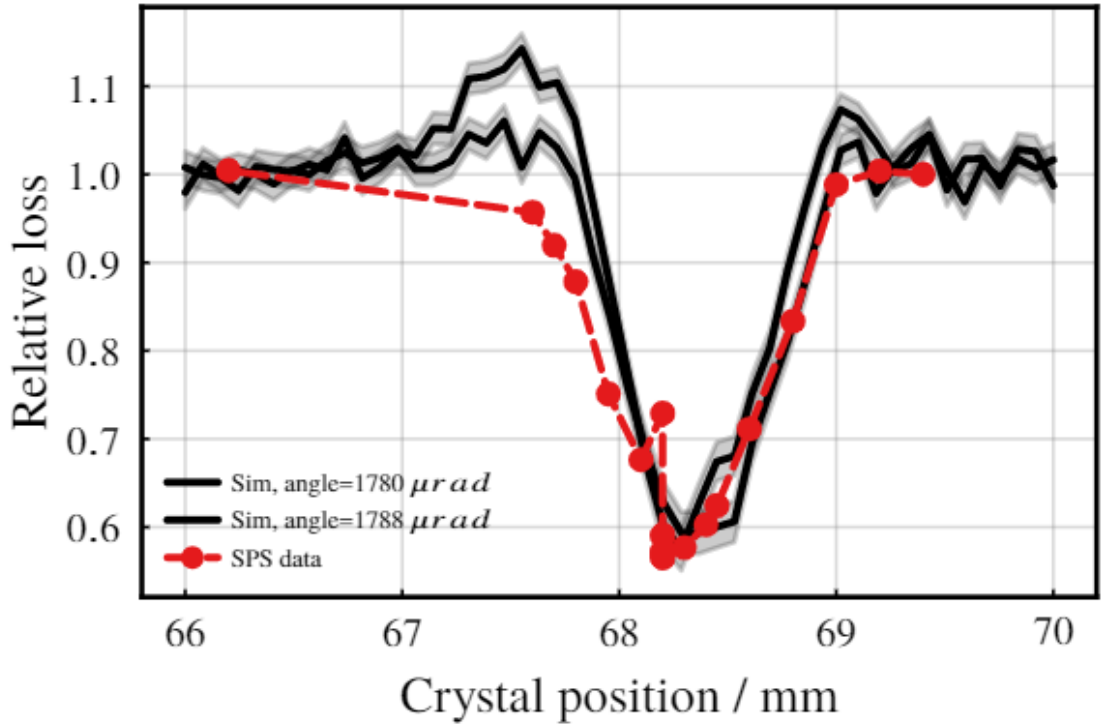
Experimental results: VR

- Linear scan of crystal position in VR (-15 μrad deflection): 20% gain
- 500 μm ES width fitted from shape (narrow beamlet is scanned across ES)



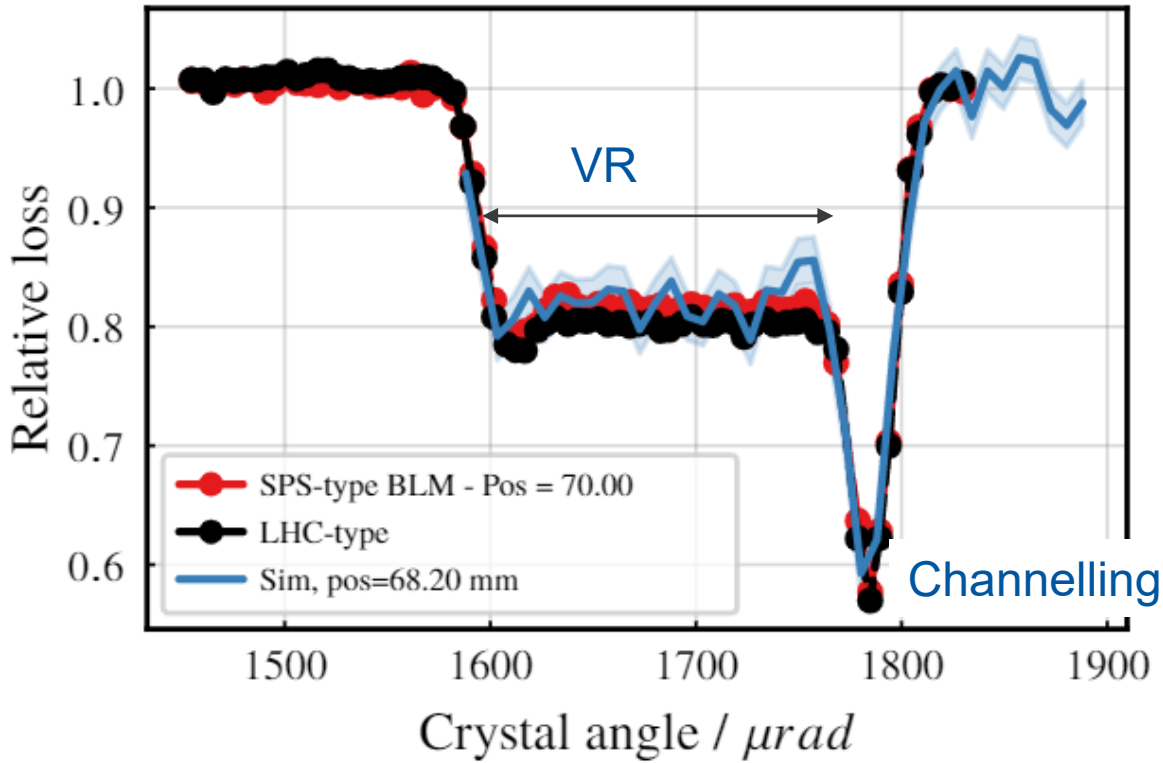
Experimental results: channelling

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



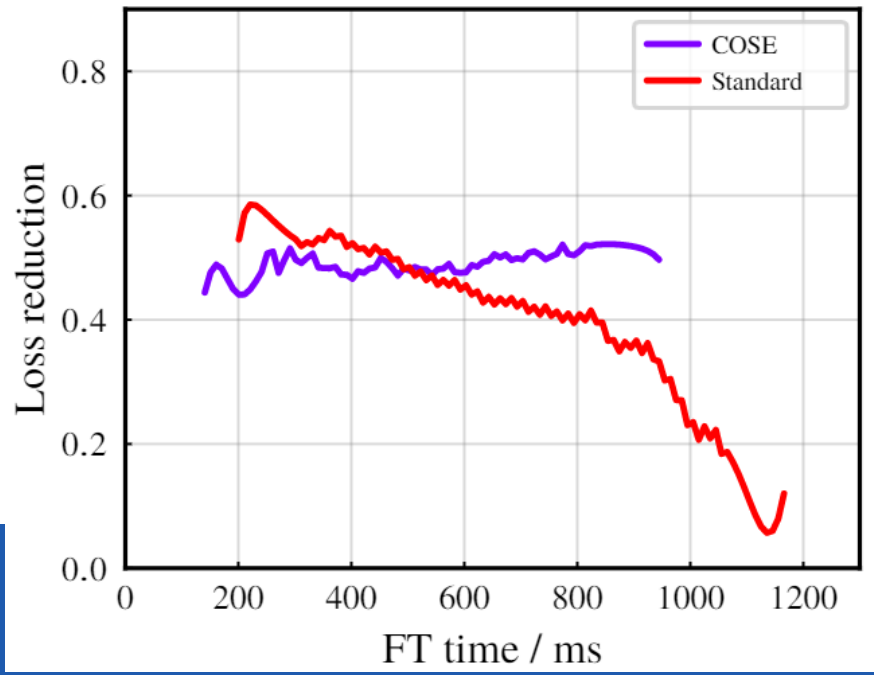
Experimental results: angular scan

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



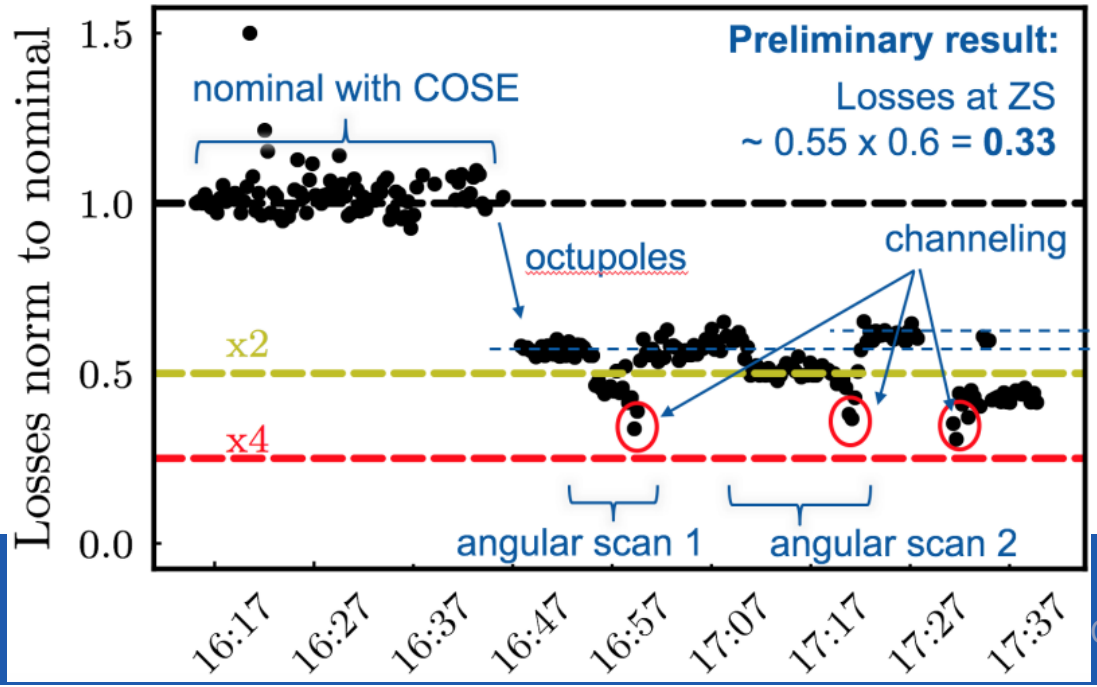
Experimental results: time resolved losses

- 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



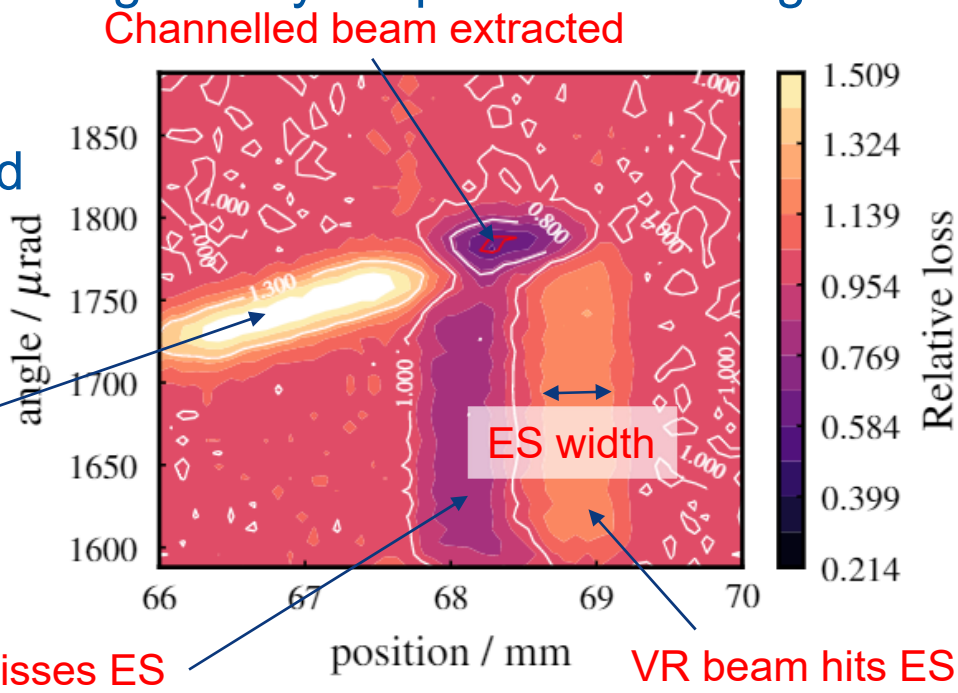
Experimental results: crystal + octupoles

- 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?



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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