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

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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 $4 \times 10^{19}$ PoT/y, 350 kW beam power: similar to CNGS but with slow extraction

• Present 400 GeV slow extraction of $1.3 \times 10^{19}$ 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

- Extract 400 GeV protons over ~seconds with 3\textsuperscript{rd} integer resonance
- Thin electrostatic wire septum: 16 m long, 11k 60-100\textmu 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 $\mu$rad - would need a $\sim$120 T magnetic field
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 $5.4 \, \mu\text{rad (1}\sigma\text{ rms)}$
- Extraction with Q-sweep and large $\delta p/p$ gives separatrix rotation in spill
- With Q_sweep separatrix angular width $12.3 \, \mu\text{rad (1}\sigma)$. 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 $\pi^+$)

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, $5 \times 10^{12}$ p/spill
- SEM grid profile upstream ES shows density reduction in channelling

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

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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 \( \mu \text{rad} \)
- Best loss reduction 44%
- Optimizer input?

Channelled beam hits ES

Channelled beam extracted

VR beam misses ES

VR beam hits ES

ES width
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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