Accelerator developments for SHiP and FCC

Linda S. Stoel

With input from M. Benedikt, M.A. Fraser, B. Goddard, R. Jacobsson, V. Kain and F.M. Velotti.
SHiP and FCC

- Explore two different regions of potential new physics
Resonant slow extraction

- Exploit a resonance for controlled amplitude growth in order to extract a beam in secs/mins
- Used at CERN PS since late '60s, SPS late 70's
- Recent slow extraction workshop in Darmstadt allowed comparison of techniques used at different labs, working on a comparison list.
Resonant slow extraction in SPS

- Uses a third order resonance ($Q_x \approx 26.66$)
- Stable phase space area depends on tune and thus (via chromaticity) on momentum
- The tune is swept so particles of different momenta become resonant and are extracted

\[ |Q_1 - Q_{\text{res}}| > |Q_2 - Q_{\text{res}}| > |Q_3 - Q_{\text{res}}| \]
Resonant slow extraction losses

- Losses are inherent to slow extraction, since the septum will intercept part of the extracted beam.
- Loss can be minimized by:
  - Spiral step (increase)
  - Septum thickness (thinner)
  - Angular spread at septum (decrease)
  - Septum length (shorter)
SHiP - Introduction

• Additional 390 GeV fixed target experiment
• Aim to explore domain of “hidden particles” with masses in the MeV – GeV range (heavy neutral leptons, dark photons, light scalars, supersymmetric particles, …)
• $2 \cdot 10^{20}$ p^+o.t. in 5 years, same as for CNGS, but that used “loss free” fast extraction
SHiP - Requirements

- Hidden particle production in $\pi$, K, D, B decays, coupling to photons, … → High A and Z target
- Production branching ratios of $O(10^{-10})$ → Largest possible number of protons
- Long lived objects → Large decay volume
- Hidden particles travel unperturbed though ordinary matter → Allows filtering out background

⇒ Detector pileup is no issue, but the power deposited in the target necessitates slow extraction
SHiP - Proposed timeline

- Technical Proposal submitted in 2015
- Comprehensive Design Report in 2018
- ~ 5 years of construction
- 5 years of data taking, starting in 2026, after Long Shutdown 3.
SHiP - Beam transfer

- 7.2 s slow extraction cycle, 1.2 s flat-top
- $4 \cdot 10^{13} \text{ p}^+ / \text{cycle at } \sim 390 \text{ GeV/c}$
- $4 \cdot 10^{19} \text{ p}^+ \text{o.t.}/\text{year, and } 1 \cdot 10^{19} \text{ shared among other North Area targets}$
- Main challenges lie in slow extraction:
  - $4 \cdot 10^{13} \text{ p}^+ / \text{cycle is historical maximum extracted}$
  - Typical flat-top length 4.8 s
  - Factor 2 increase in p$^+$/year (from historical record)
SHiP - Radiation concerns

- Already the first septa are electrostatic wire septa with wire thickness 60 μm (alignment error similar), not much more to gain

- Activation is already a big issue, and it is roughly linear in number of protons extracted, unless other improvements are made
SHiP - Spill stability

- Autospill application to find the right tune-change function
- Power supply stability: 50 Hz harmonic correction is applied regularly and is under study
- Other noise frequencies at large amplitude are sometimes observed for long periods of time, but not understood yet
SHiP - Recent developments

- ZS alignment and realignment
- SPS Quality Check (Software interlocks on losses per proton for each extraction)
- 50 Hz harmonic corrections
- First test of SHiP cycle
SHiP - Future developments

- Improved reproducibility in dynamic, multicycling machine? (feedback/feedforward)
- Machine Development studies to investigate
  - RF effects
  - Applying Hardt condition
  - Dynamic extraction bump
  - Effects of momentum spread
  - Crystal-assisted slow extraction
  - ...
SHiP - Crystal assisted SE

- Use a crystal to give a kick to particles that would end up hitting the septum, so that they reach the extraction channel: “shadowing”.

![Graphs showing the impact of delta p on the X/\sqrt{m} plane]
FCC - Introduction

• Study aimed at 100 TeV centre of mass pp-collider, but includes other machines too.
FCC - Proposed timeline

- Currently studying many options to find an optimal baseline design, which will be studied in detail
- Prepare conceptual design report for end 2018
- Aim to start as soon as possible after HL-LHC ends (2035)
FCC - Accelerator options

- FCC-ee at several energies
  - 90, 160, 240 and 350 GeV, for Tera-Z, Oku-W ($10^8$), Mega-Higgs and Mega-top
- FCC-hh with booster
  - HEB@LHC, ~ 3.3 TeV
  - HEB@SPS, ~ 1.5 TeV
  - HEB@FCC, ~ 3.3 TeV
- Potential FCC-eh option added
FCC - Fixed target opportunities

• HEB provides interesting opportunities when FCC is in stable beams
  - Large amounts of particles at 1.5 or 3.3 TeV

• If LHC is not in the injector chain, it could be used for fixed target experiments
  - Large amounts of particles at up to 6.5 TeV

• FCC itself may present an opportunity via crystal halo extraction
  - Low amounts of particles at 50 TeV
FCC - Experience

- Resonant extraction: SPS, 400 GeV, $7.3 \cdot 10^{12} \text{ p}^+/\text{s}$ operational, $3.3 \cdot 10^{13} \text{ p}^+/\text{s}$ proposed
- Collider driven crystal extraction: Tevatron, 900 GeV, $1.5 \cdot 10^5 \text{ p}^+/\text{s}$ ($10^{12} \text{ p}^+$ in collider)
- “Kick mode” crystal extraction: Tevatron, 900 GeV, $10^8-10^9 \text{ p}^+/\text{kick}$ for $10^{11} \text{ p}^+/\text{bunch}$
- Several design ideas for SSC (20 TeV)
- $\rightarrow$ TeV scale slow extraction needs some R&D
FCC - 50 TeV extraction

• An array of crystals could be used to extract particles from the FCC beam halo [1]

• Could provide particles for fixed target physics that would otherwise end up in collimation

• Improvements in goniometer accuracy and improved simulations needed.

• Extension of LHC crystal halo collimation and SPS crystal extraction studies?

[1] Bent crystal extraction from a 100 TeV proton collider; A.D. Kovalenko, W. Scandale and A.M. Taratin; NIMB; 2015.
FCC - HEB resonant extraction

• Activation concerns for the first septum (crystal shadowing, massless septa?)
• Activation concerns for “beam splitting”
• High energy (collider) rings tend to have small apertures and a collimation system → not much space for the resonant particles to oscillate
  - HEB@SPS is looking into large aperture
  - Possible “spiral step” depends on aperture, so aperture influences losses at septum
FCC - HEB resonant extraction

- Longer cycle times mean short spills do not make much sense (duty factor)
  - 0.5-4 min ramp up+down for HEB, 20 min for LHC
  - For long spills without RF, energy loss due to synchrotron radiation needs to be taken into account (bunched extraction will influence spill structure)

- An “abort gap” is necessary to be able to safely dump the beam at any time
  - Will influence the spill structure at $f_{\text{rev}}$
FCC - Slow extraction options

- Still many different machines/energies to consider
- Amplitude growth by natural halo repopulation, resonance, noise on magnet or by the damper
- Using thin/massless septa, crystals or both
- Input from experimental community important as input for design choices (!)
  - Desired intensity per year and spill rate, tolerance of momentum change/spread, etc.
Conclusions

• Many developments ongoing at SPS to improve the existing slow extraction, for present operation and for SHiP
  – Studies to improve alignment, understand reproducibility, use crystals, etc.

• TeV scale FT beams may become available
  – Activation and aperture are main concerns
  – Input on beam requirements much appreciated

• Wide range of options to be studied
SPS orbit stability

- For LHC extraction (450 GeV), July-October
High Energy Booster specs

<table>
<thead>
<tr>
<th></th>
<th>LHC x5</th>
<th>HEB@SPS</th>
<th>HEB@FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>3.3 TeV (1-6.5)</td>
<td>1.5 TeV</td>
<td>3.3 TeV (1-5.5)</td>
</tr>
<tr>
<td><strong>FCC filling time</strong></td>
<td>40 min</td>
<td>34 min</td>
<td>29 min</td>
</tr>
</tbody>
</table>

(FCC-hh design has ~ $10^{11}$ p+ per beam)
Synchrotron radiation

![Graph showing relative energy loss over time for different synchrotron radiation systems. The graph includes lines for FCC: 50 TeV, 16 T, LHC: 6.5 TeV, 7.8 T, "HEB@LHC": 3.3 TeV, 4 T, "HEB@FCC": 3.3 TeV, 2 T, and "HEB@SPS": 1.5 TeV, 7.5 T. Time intervals are marked at 30 s, 5 min, 1 h, and 5 h.]