Joint Accelerator Performance Workshop 2022
Slow extraction improvements

Pablo Arrutia

Many thanks to the SPS & PS Operations Teams, all equipment groups, the NA62 experiment and everyone who helped me with this talk:
Intro

Slow extraction improvements and R&D in 2022 aimed at addressing IEF WS 2021 feedback (and more):

- ‘Review fast spill monitoring across complex’
- ‘Add planned periods to work with Experiments on spill structure in SPS - MDs or commissioning time’
- ‘Improve spill structure and monitoring in PS and SPS’: ‘Spill structure (spike, harmonics) and monitoring “flatness of spill and duty cycle as important as intensity”’
Intro

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Simulations interfacing slow ripple with RF structure

The virtuous loop of slow extraction

Metrics well-aligned with experimental request

Instrumentation across Hz to 100s MHz

Techniques, strategies for improvement

Controls/Optimisation

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Outline

- Empty bucket channelling (EBC)
- Non-local crystal shadowing
- Other topics
Empty Bucket Channelling (EBC)

My Bucket List
- Get an Empty Bucket
RF cavities turned on during extraction, with a frequency offset from beam.

Particles channel between empty buckets -> coherent kicks.

EBC improves spill quality across entire low-frequency spectrum.

Ripple suppression region identified during July MDs -> Move towards operational tests.
Spill quality improvements

- **Ripple reduction by 5x**, without auto-triggering the feed-forward optimiser. Confirmed by experiments:

  - Operational test data
  - NA62 data

Typically at 1300/1500, at ~1000 with EBC

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Beam loss

- Beam losses can be kept under control.
- Manipulation is compatible with crystal shadowing as long as RF voltage kept modest. Otherwise, increase angular spread -> decreased efficiency.
SPS machine stability

- Variations in super-cycle (hysteresis) can mismatch the revolution frequency of the beam with respect to the optimum EBC frequency.
- Re-alignment strategies being studied, similar approaches to crystal shadowing.

Reduced suppression:

- Spike at beginning of burst

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QF/QD ripple drifts

- Power converter ripple amplitude in QF/QD drift observed during tests.
- The source of the ripple (100 Hz) needs understanding and attacking, further investigations shown later in this talk.
- EBC suppresses the ripple well but cannot stop the drift.

50, 100Hz components of QF/QD power converters current

50, 100 Hz components of spill
Control of 800 MHz system at FT

The 200 and 800 MHz frequency programs cannot be controlled independently:

- Optimal settings for 200 MHz debunching compensation and optimal settings for 800 MHz EBC are in conflict
- Optimising the 800 MHz system for EBC leads to some 200 MHz structure during the debunching
- No 800 MHz structure apparent

Proposal: switch 800 MHz system to independent fixed frequency at SFTPRO FT.
**Dumped intensity**

**Dumped intensity higher than operational** for certain scenarios. Possible sources:

- Some beam is trapped inside bucket (after super-cycle change).
- Some beam crosses resonance too fast to be extracted. Simulations predict < 1% impact from this effect.
Open points and follow-up

• Initial iteration with RF suggests no apparent show-stoppers for the requested 800 MHz feature, but implementation requires work so priority must be understood.

• Systematic approach of empty bucket re-alignment must be produced, either with automated tools or with written procedure. Consists of simple trim offset on frequency. Goes hand-in-hand with machine stability improvements (hysteresis)
Non-local Crystal Shadowing

Courtesy of F. Velotti

No, not that kind of crystal...
Non-local shadowing: **Exploit non-linearities and multi-regime effect to optimise loss reduction** at the ZS via thin crystal.

To obtain a x4 loss reduction, simulations show that a 1.8 mm thick crystal was needed.

Only crystal available at the moment was same as in LSS2 (TECS) → 0.8 mm

Installed in LSS4 on new goniometer during last YETS.
October MD

- Only TECA, non-local shadowing in LSS4.
- Clearly seen that TECA touches more regimes at once (VR, AM, CH) → in case largest part of separatrix is in CH, loss reduction of ~20%
- When optimal sharing between CH+VR+AM → largest loss reduction ~45%

![Graphs showing AM, VR, and CH scans with loss data](image)
November MDs

- Confirmed that mix of regimes minimises losses.
- Hysteresis effects observed between stops.
- Combining both local and non-local systems brings losses down by 51%! 

![Graph](image-url)
Open points and follow-up

- **Large error in crystal movement**
  - Fully dominated the first measurements campaign.
  - Great improvements for the last MD → finally possible to perform scans (e.g. linear).
  - Crystal angular resolution ~10 urad, we need less to accurately probe channelling deep.

- Denser separatrix at TECA location → **high losses in LSS4 as expected**
  - Operational test postponed to next year – need another *discussion with RP*.
  - Probably mask needed → detailed simulations of the expected activation and shielding needed before next year commissioning.

- Propose to do **operational test** (TECA in for about 24h) **on first days of physics**.

- **Awaiting for 1.8 mm crystal to move towards 4x loss reduction.**
Other topics
PS: a great test bed

- **PS higher MD availability and lower risk of equipment damage extremely useful for tests.**
- EBC first implemented in PS, **results translated very well to SPS.**
- See M. Delrieux’s talk for more examples.
- Crucial addition: dBLM during upcoming YETS (thanks to PBC support).

RF structure

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SPS: OP tools, non-OP features

Current auto-spill 50 ms resolution introduces some ripple at 20 Hz, reported by NA62. Suggestions:

- Feature to add low-pass filter to central portion of correction trim.
- Increase resolution (Moves problem to new freq.).

Current freq default behaviour causes freq. jump when loops go off -> not optimal for 200 MHz compensation.
SPS: Power converter analysis

- Power converter stability key component of high-performance slow extraction.
- Investigation of all relevant frequency spectra performed before and after spill deterioration (May 12th 2022).
- No obvious culprits found among quads, dipoles and chromatic/harmonic sextupoles.

**F-quad analysis**
Simulation/tooling

- Computational tools play crucial role for understanding and improving slow extraction performance.
- i-FAST REX WG led by F. Velotti for simulations on slow extraction.
- **Xsuite effort is being supported** and simulations are being benchmarked and ported, exploiting GPU capabilities and python flexibility.
- **EBC tests in SPS in great agreement with simulation predictions** -> potential for model-based optimisation.
Fast instruments & work with experiments

- Pushing for fast detection devices if experiments need uniformity in the 100s MHz scale - progress on dBLM and OTR during EBC MDs.
- Established workflow with NA62 to exploit their ~70 ps acquisition systems during MDs and tests for EBC.

F. Roncarolo et al
Conclusions & Further Work

• **EBC with 800 MHz system demonstrated 5x ripple improvement**, re-alignment needs addressing, RF frequency offset feature is important.
• **Non-local shadowing combined with local shadowing cut ZS losses in half**, RP considerations for LSS4 on-going, operational test next year.
• RF manipulations to **increase momentum spread** being tested -> faster tune sweep.
• **Noise techniques to be investigated** in PS to extract with fixed magnetic elements (to remove slow drifts) and in SPS to further improve spill quality.
• Will **revisit octupole folding** in SPS in context of ECN3 HI facility to further reduce ZS losses.
• Recommendation: **compile NA & EA spill requirements and limits** in 'common language'.

**Noise techniques**

Boussard et al.

**Octupole folding**

M. Fraser

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THANK YOU.
EXTRA SLIDES
EBC
Phase displacement BU

Before

\( \Gamma = 1.5, \text{ turns} = 445 \)

After

\( t \text{ [s]} \)

\( \delta \text{ [T]} \)
EBC, Simulation: 200 MHz

**Ripple suppression**

Reductions of up to 2 orders of magnitude predicted by simple simulation model.

**Limitations**

High voltages can perturb beam, need to keep it in mind.

- Beam size blow-up -> Losses
- Beam bunching -> event overlap

1 period of 200 MHz
EBC, Measurements: Ripple suppression

200 MHz

800 MHz

\[ F = \frac{\langle I(t) \rangle^2}{\langle I^2(t) \rangle} \leq 1 \quad \text{(DC power) : (Total Power)} \]
Non-local shadowing – optimisation
November MD

- Complete linear scan and angular scan focusing in shadowing
  - Many angular scan but beam not very stable
  - After AM scan, clear movement of relative alignment of TECA and ZS
  - Loss reduction obtained with TECA only in the same order of previous MD → ~45%

![Graphs showing linear and angular scans with loss vs. TECA position and angle]
Global loss reduction (unsplit optics in TT20)
Non-local crystal scans
Empty bucket channelling MDs in the PS

- Channelled the beam without extraction both with sinusoidal buckets and barrier buckets:

- Implemented channelling in slow extraction to the EAST area to improve spill quality: