SPS slow-extraction: Challenges and possibilities for improvement

Physics Beyond Colliders Kick-off Workshop
6 – 7th September 2016

Matthew Fraser and B. Goddard, TE-ABT
On behalf of B. Balhan, J. Borburgh, K. Cornelis, V. Kain, L. Stoel, F. Velotti
Extraction from SPS for FT physics

- Slow-extraction is used to deliver a **constant flux of particles** to Fixed Target experiments over many seconds from a synchrotron:
  - From SPS we typically extract up to $\approx 3 \times 10^{13}$ $p^+$ during 4.8 s, i.e. whilst beam circulates for over 200,000 turns
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- Unlike single or multi-turn extraction, the slow-extraction process is **intrinsically lossy**:
  - We cannot (yet!) create a clear temporal or spatial separation in the beam to extract cleanly
  - In fact, most FT experiments **don’t want temporal structure** in the beam!
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- Beam loss from slow-extraction is **unavoidable**, and has to be **controlled** and **optimized**:
  - Induced activation in Long Straight Section 2 (LSS2) increases in direct proportion to the beam loss on the septum
The slow-extraction scheme

- Beam deliberately excited using a **third-order resonance** and large amplitude particles extracted with a thin **electrostatic septum** [ES]:

![Diagram](image_url)
The slow-extraction scheme

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![Diagram of extraction process]

- $x, y, z, E$
  - $d = V = -220 \text{kV}$
  - Septum Wires
  - Electrode
  - Extracted Beam
  - Circulating Beam
  - Septum wire

[1]
The slow-extraction scheme

- Beam deliberately excited using a **third-order resonance** and large amplitude particles extracted with a thin **electrostatic septum** [ES]:

![Diagram showing beam extraction](image1)

\[ x_yz \]

\[ E_dV = -220 \text{ kV} \]
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![Diagram of extracted beam and septum](image1)

- Circulating Beam
- Septum Wires
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\[ V = -220 \text{ kV} \]
The slow-extraction scheme

- Beam deliberately excited using a **third-order resonance** and large amplitude particles extracted with a thin **electrostatic septum [ES]**:

![Diagram of beam extraction](image)

- Losses (~%) from beam impact on wire

![Diagram of beam and septum](image)

- Circulating Beam
- Septum Wires
- Electrode
- Extracted Beam

\[ V = -220 \text{ kV} \]
The slow-extraction scheme

- Beam deliberately excited using a **third-order resonance** and large amplitude particles extracted with a thin **electrostatic septum** [ES]:

- Resonant tune \[ Q = 26.666… \] swept across the tune spread of the beam by varying the QF current:

\[
\frac{\Delta p}{p} \propto -\Delta Q
\]

momentum spread, tune

- Schottky measurement during spill, courtesy of T. Bohl

---

M.A. Fraser, TE-ABT-BTP

PBC Kick-off Workshop, 6 - 7th September 2016

Slide 3/15
The slow-extraction scheme: LSS2

- Extraction geometry designed in 1970’s and largely unchanged:

Trajectories for third-integer resonant slow extraction in LSS2 (Q26.666...)

5 tanks ≈ 20m

To TT20 and NA
The slow-extraction scheme: LSS2

- Extraction geometry designed in 1970’s and largely unchanged:

![Diagram showing trajectories and components of the extraction system]

The electrostatic septum: ES
The slow-extraction scheme: LSS2

- Extraction geometry designed in 1970’s and largely unchanged:

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<table>
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- 5 tanks ≈ 20m
- W-Re wires 60 – 100 μm
- To TT20 and NA

The electrostatic septum: ES
POT delivered and requested

- Since restarting after LS1 some of the highest proton (p) fluxes have been extracted to the North Area in ≈10 years.
POT delivered and requested

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- High intensity requests from NA are continuing into 2016...

![Diagram showing POT delivered and requested for various years from 1995 to 2016.](image-url)
POT delivered and requested

- Since restarting after LS1 some of the highest proton \((p)\) fluxes have been extracted to the North Area in \(\approx 10\) years.
- High intensity requests from NA are continuing into 2016...
- Future experimental proposals request as much as \(4E19\ p/yr\) over 5 years:
  - Same as delivered to CNGS (so OK for SPS) but a fast and almost loss-free extraction process was used (\(2x\ 10.5\ \mu s\) spills per 6 s).

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<table>
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<th>NA (third-integer ext.)</th>
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</tbody>
</table>
```

LS1: start up end of 2014

1.1E19 pot requested for 2016

?
Activation induced by slow-extraction

- Rough **rule-of-thumb** for activation since the early 1990’s:
  - end of run activation in LSS2 at ES is linear with the p.o.t. delivered that year

Dose rate measured next to the ES (at ≈ 80 cm) **30 hours** after SPS proton operation ceases

*Sensitive to exactly when FT operation ceases and extraction rate at end of the run*
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Dose rate measured next to the ES (at ≈ 80 cm) 30 hours after SPS proton operation ceases (sensitive to exactly when FT operation ceases and extraction rate at end of the run)

- SPS Losses and Activation Working Group (SLAWG) was formed to investigate and follow-up the increase in activation during 2015
Challenges encountered since LS1

- SPS is becoming a truly **multi-cycling** machine:
  - Frequent super-cycle (SC) changes and dynamic economy cycles induce hysteresis effects that **move the beam alignment with the ES**
  - ES cannot be quickly re-aligned in response to SC changes
  - Optimization of the extraction efficiency is time-consuming
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  - The slow-extraction is a **resonant process** and it amplifies the **smallest imperfections** in the machine:
  - e.g. spill intensity variations can be explained by ripples in the current (mains: n x 50 Hz) at the level of **a few ppm**!
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- **Interventions** on extraction hardware in **activated area**
Mitigation measures implemented

- FT cycle now included in **SPS Quality Control** application:
  - Online **monitoring** of the per proton extraction losses
  - **Interlocked** thresholds (SIS)
  - **Re-alignment** of the ES when loss levels rises significantly (monthly)
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  - Reporting to IEFC [7]
  - Actively working on a longer term strategy for loss mitigation
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- **Collaboration with UA9** formed to investigate the use of crystals for slow-extraction at the SPS:
  - First MD was successfully carried out in July, with a second planned in October
Spill quality

- Low frequency noise on the QF power supply reduces the effective spill length for experiments:

A recent example of a relatively good spill with large $n \times 50$ Hz components and another noise source at 10 Hz [8]
Interventions and maintenance of ES

- RP limits for personnel are becoming stricter, with good reason!
  - If machine activation is not reduced, longer cooling times will have to be accepted for interventions on the extraction equipment: **impact on machine availability**
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- Interventions in high radiation areas are necessary [9]:
  - **Remote handling**: employed for first time in 2016, has to be the future direction
  - Steep learning curve in 2016: **dose taken reduced by factor 2**
  - Number of interventions is **ultimately limited** by dose taken by trained personnel (< 2 mSv/yr/person) and has to be shared with interventions across CERN complex

- ES tank 4 exchange, 9 Feb 2016: 3.3 mSv (collective dose)
- ES tank 2 exchange, 19 Feb 2016: 1.7 mSv (collective dose)
- Remote handling in LSS2
Impact of future POT requests

- We must **improve the extraction efficiency** by more than a factor 3 to keep an **ES exchange** intervention within reasonable RP limits (below **ALARA III** [10]):
  - As projected by our rule-of-thumb...for a flux of 4E19 p/yr
  - ...allowing a 1 week of cool-down period before intervention
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- Bear in mind that **during 2015** we would have had to wait **1 month** with the above assumptions:
  - Able to wait 3 months into the YETS, but not to be repeated...!
Active research avenues

- Removing *sensitivity* of slow-extraction to *super-cycle changes*:
  - Exploitation of a calibrated *SPS B-train* will be indispensable
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- Phase-space density reduction:
  - separatrix folding, SPS optics, massless septum, e-lens, ...
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- Doctoral student in TE-ABT since March 2016
Collaboration between TE-ABT and UA9

- Shadowing the ES septum wires using an upstream crystal to coherently channel particles away from the wires and into the septum gap [11,12]
- First (non-local) tests could be made relatively soon (2018?) with a crystal installed in LSS4:

- Challenge: transporting channeled beam to target (or dump)

Crystal in LSS4 (channeling) ≈1 mm wide, Δx’ ≈150 μrad
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Preliminary studies show a promising loss reduction:

\[ \delta_p / 10^{-3} \]

\[ \text{particles / extracted particles} \]

\[ \text{spill time [s]} \]

\[ 4.8 \]

\[ 1000 \]

\[ 10^2 \]

\[ 10^1 \]

\[ x / \text{mm} \]

\[ 50 \]

\[ 85 \]

\[ \text{nominal} \]

\[ \text{crystal} \]

\[ \text{ES} \]
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![Graph showing loss reduction](image.png)

Particle density at ES:

- Blue and red lines represent nominal and crystal conditions, respectively.
- The graph shows a decrease in particle density when using a crystal.

- Collaboration between TE-ABT and UA9
- PBC Kick-off Workshop, 6 - 7th September 2016
Summary

• Slow extraction is only way to give a 1 second spill, but is intrinsically lossy (few % of beam)

• Delivering 4E19 pot/yr via LSS2 slow extraction needs factor 3 - 4 reduction in local activation

• Working group (SLAWG) established in 2016 and actively tackling the issue (already for today’s beams)

• Promising beam loss reduction options exist and are being actively studied

• SPS instrumentation, stability and reproducibility have to improve in parallel
Thank you for your attention
References

[4] F. Velotti, Orbit stability during LHC extraction, MSWG Meeting, CERN, 27 May 2016,
[8] V. Kain, SLAWG Meeting #5, CERN, 1st September 2016
[10] M. Fraser, Update on SPS LSS2 extraction losses and activation, 168th IEFC Meeting, CERN, 2016
[12] F. Velotti et al., Slow extraction assisted by bent crystals in the SPS Meeting, 28 July 2016
Extra slides
Mandate of SLAWG

- **Analyse and document** historical and current **beam losses** in SPS and TT20 as a function of beam type and year
- Define key **reference interventions with WDP** and reasonable cool-down times as a function of activation level
- Follow up improvements in SPS **logging and surveillance tools**
- Propose target **interlock** levels for losses per proton for LSS2 slow extraction
- Deploy **surveillance SW to interlock beams** for excessive extraction losses
- Study **short and long-term methods to improve** extraction, transport and splitting losses
- Liaise with **LIU and CONS projects** for common developments/improvements
- **Analyse required p.o.t.** requests from NA experiments and define implications for SPS operation
- Periodically **report status and results** to IEFC
SPS Quality Check (QC)

- Factor ≈ 2 increase in activation went unnoticed because the per cycle extracted beam intensity was lower, compared to 2012, but the duty factor higher.

- FT cycle now included in SPS QC application:
  - Online monitoring of the per proton extraction losses
  - Interlocked thresholds (SIS)
  - Regular re-alignment of the ZS during dedicated MD

![SPS QC monitoring application after first ZS alignment in 2016](image)

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<td>2.1</td>
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Recent normalised extraction losses (averaged over the year)
SPS Autospill [6]

- Servo quad feedback with intensity measured in extraction line disconnected to improve trajectory stability in transfer line:
  - Shot-to-shot orbit variations amplified by servo quad
  - Feedback sensitive to cycle-to-cycle intensity variations
  - Small dimension of NA62 target in 2015 sensitive to steering errors

- Instead, feed-forward on current in main quadrupole (QF) circuit using Autospill application:

  Symmetry measured on T4 target:
  - Servo feedback: 1 Dec 2014
  - SMQ feed-forward: 1 Oct 2015

Symmetry (at target): 100% = centred
QF Glitches

- Small current glitches ($\Delta I \sim 1$ in 2000 A) observed recently during slow extraction: sporadic and, to date, without explanation
- Glitches of $\Delta I/I \sim 10^{-3}$ seriously disrupt the slow-extraction

Glitch on 2nd October 2015

Glitch on 24th April 2016
QF Glitches

- Small current glitches ($\Delta I \sim 1$ in 2000 A) observed recently during slow extraction: sporadic and, to date, without explanation
- Glitches of $\Delta I/I \sim 10^{-3}$ seriously disrupt the slow-extraction
- Under investigation!

A classic glitch event on 9th July 2015: current sharply increases before regulation loop kicks in

Scope installed on SMQ to trigger acquisition to diagnose source of glitch
ALARA III (see 88th IEFC, 2013, H. Vincke)

https://edms.cern.ch/document/1296520/1

![Image of ALARA criteria]

CRITÈRE DE DOSE INDIVIDUELLE

Équivalent de dose prévisionnel individuel ($H_i$) pour l'intervention, ou pour l'ensemble des interventions de même nature lorsque celles-ci sont répétées plusieurs fois sur une année :

- 100 μSv
- 1 mSv

niveau I | niveau II | niveau III

CRITÈRE DE DOSE COLLECTIVE

Équivalent de dose prévisionnel collective ($H_c$) pour l'intervention, ou pour l'ensemble des interventions de même nature lorsque celles-ci sont répétées plusieurs fois sur une année :

- 500 μSv
- 5 mSv

niveau I | niveau II | niveau III
ALARA III (see 88th IEFC, 2013, H. Vincke)

ALARA limits:
- 5 mSv collective dose per intervention
- 1 mSv individual dose per intervention
- Hard limit dose to individual is 2 mSv/yr

Waiving of the ALARA committee meeting

Circumstances

- Repetitive intervention
  - A procedure has been worked out under which circumstances a waiving of the ALARA committee meeting could be possible
  - Generic DMRs should be worked out and approved a priori in an ALARA committee meeting.

- Urgent maintenance/repair
  - ‘Urgent ALARA committee’ decision
  - No ‘formal (physical)’ ALARA committee meeting required
  - Generic DMRs for standard maintenance/repair should be worked out and approved a priori in an ALARA committee meeting.

https://edms.cern.ch/document/1296520/1
SPS orbit stability (LHC cycle at extraction)

- Drifts of ~ mm observed over months (July to October 2015) [4]
RP survey LSS2: example in 1998

Peak at ZS extracted and plotted as function of p.o.t. for that year
MEMORANDUM

To: Walter Scandale, Chairperson of the UA9 Collaboration

From: Frédéric Bordry, Director for Accelerators and Technology

cc: Paul Collier, Head of the Beams Department
    José Miguel Jiménez, Head of the Technology Department
    Roberto Saban, Head of the Engineering Department
    Brennan Goddard, TE-ABT Group Leader

Subject: Slow extraction assisted by bent crystals in the SPS

Following the interest generated by the Proposal for Investigating Slow Extraction Assisted by Bent Crystals in the SPS, I would like to ask the support of the UA9 collaboration both for the studies and for the developments of hardware and software which these might entail.

Needless to say, the beam time required for the validation of the concept will be taken from
Dynamic Economy at SPS

SPS Ring

a) Dynamic economy

The main power supply and RF power will execute a modified (energy saving) function if the BCT does not detect the beam after the first injection.
- MPS staying at injection energy.
- All ring circuits staying at Imin.
- All transfer line circuits without TT10 staying at Imin.

If the FGCs receive a trigger dynamic eco.
The FGCs staying at the injection energy and play a smooth function to reach the last configurable point and to keep the same magnetic history.
We can force the pulse by hand to do some check.

Bent crystals for UA9

**Quasimosaic crystal**
- Bent along (111) planes
- Minimal length a few tenths of mm
- Non-equidistant planes $d_1/d_2 = 3$

**Strip crystal**
- Bent along (110) planes
- Minimal length ~ 1 mm
- Equidistant planes

**Crystals**
- Dislocation-free silicon crystals plates or strips
- for optimal channeling efficiency
  - short length (few mm)
  - moderate bending radius 45 ÷ 70 m
- Mechanical holders with large C-shape frame imparting the main crystal curvature
  - Strip crystal: (110) planes are bent by anticlastic forces
  - Quasimosaic crystal: (111) planes are bent by 3-D anticlastic forces through the elasticity tensor
- Expected crystal defects:
  - Miscut: can be $\approx 100 \mu$rad, but negligible effect if good orientation is applied
  - Torsion: can be reduced down to 1 $\mu$rad/mm $\Rightarrow$ UA9 data in the SPS North Area
  - Imperfection of the crystal surface: amorphous layer size $\leq 1 \mu m$

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Multi-crystals as a septum

- Multi-crystal arrays using volume reflection proposed as septa:

  - Thickness: 1-4 mm
  - CH deflection angle: 60-150 μrad
  - MVR deflection angle: ≈ 60 μrad
  - Open area: ≤ 5 x 20 mm²