CERN

Slow Extraction R&D at CERN

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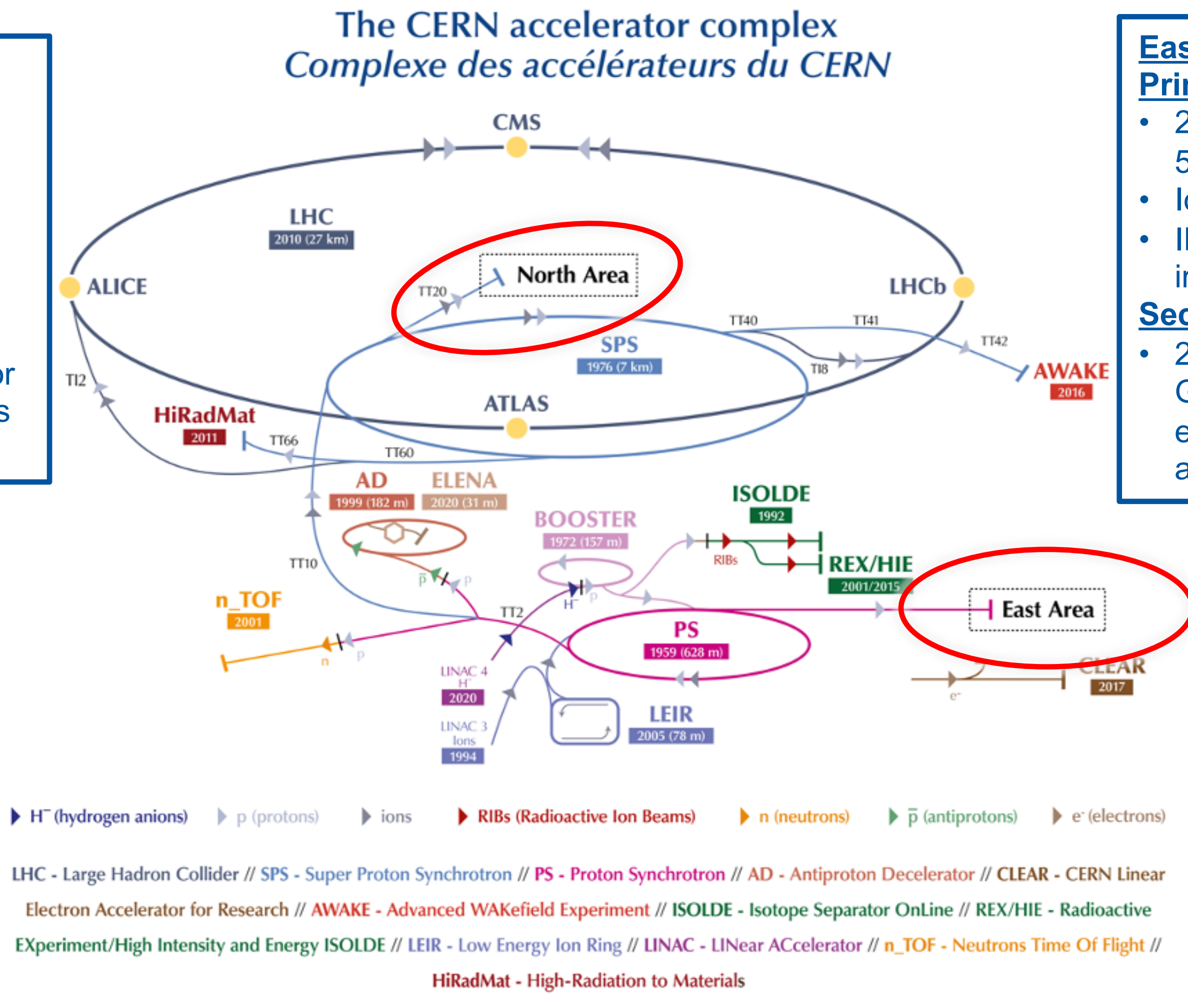
Talk Outline

- Brief overview of CERN's SX systems
- Recent slow extraction R&D achievements
  - Beam loss reduction
  - Machine stability, reproducibility and spill quality
  - Beam dynamics simulation tools
- Beam instrumentation status
- Future R&D and ideas for collaboration
- Reference material

Brief overview of FT facilities (SX)

North Area
Primary beams
- 400 GeV/c p+ @ up to 4E13 ppp
- Ions (e.g. Pb, Ar,Xe) @ various momenta

Secondary beams:
- 4 targets produce < 400 GeV/c beams for experimental physics and tests



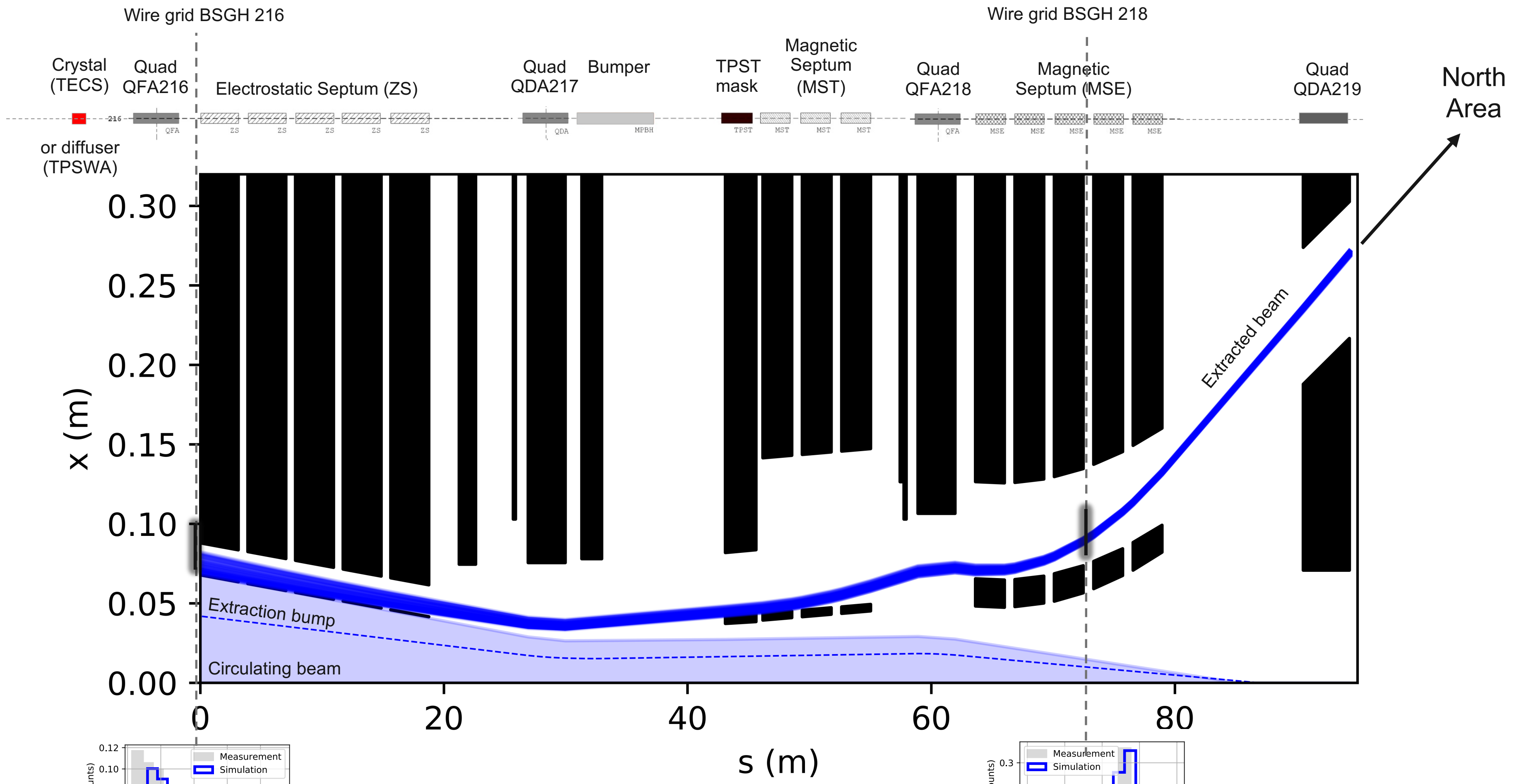
East Area
Primary beams:
- 24 GeV/c p+ @ up to 5E11 ppp
- Ions under active study
- IRRAD and CHARM irradiation facilities

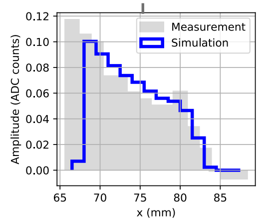
Secondary beams:
- 2 targets produce <15 GeV/c beams for experimental physics and tests

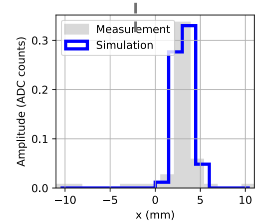
SX systems at CERN (protons)

Parameter	PS	SPS
Momentum [GeV/c]	24	400
Circumference [m]	$2\pi \times 100 = 628.3$	$11 \times 2\pi \times 100 = 6911$
Revolution period [μs]	2.1 Beam time to extraction ~0.5 ms	**23.0** **Beam time to extraction ~ 5 ms**
Transverse emittance [nm] (rms, geometric)	60	**20**
Extraction details	Tune sweep (chromatic): all magnets swept (COSE) PS close to Hardt condition at SMH, SPS ~ zero dispersion at SEH	
Third-integer tune	19/3 ~ 6.333…	80/3 ~ **26.666…**
Chromaticity at extraction [$\zeta = Q'/Q$]	- 0.5	- 1.0
Momentum spread [$\Delta p/p$] [%] (StopBand = SB)	$\pm$0.3 (SB ~ $\pm$0.1)	$\pm$0.15 (SB ~ $\pm$0.01)
Cycle length [s]	2.4	10.8
Spill length [s]	0.4	4.8 – 9.6 (1.0 tested for BDF)
Typical p^+ per cycle [10^{13}]	< 0.05	< 4
POT per year [10^{19}]	< 0.1	< 1.5
Beam power (instantaneous) [kW]	< 5	< 533
Beam power (averaged with duty factor) [kW]	< 0.25	**< 150**
Extraction inefficiency [%]	?	**~ 3**
Typical spill quality (at < 200 Hz)	?	95 %

SPS is a different scale…!







PBC requests @ SPS

See the Summary Report of Physics Beyond Colliders, CERN CERN-PBC-REPORT-2018-003

- Still a lively interest in Fixed Target physics at the SPS North Area after more than 40 years
  - Requests for higher POT have focussed SX R&D at SPS on **beam loss reduction**
- Beyond Standard Model and Dark Matter / Hidden Sector searches:
  - SPS Beam Dump Facility: SHiP **4E19 POT/yr**
  - NA62++: **1E18 POT/ yr**
  - KLEVER: **1E19 POT/yr**

North Area consolidation plans

- An ageing facility in need of consolidation, NACONS project planned for our next Long Shutdown (LS3)
- Primary beam line instrumentation is in need of consolidation
- Today's SPS experimental physics users typically want high spill duty factor across the entire frequency spectrum:
  - **SPS OP team has put in place some impressive improvements**
- Future experimental requirements will demand R&D for new instrumentation to study the extraction:
  - **Beam loss monitoring and fast spill monitoring**
- Beam Instrumentation group is doing their best to support our requests for slow extraction R&D already today:
  - <u>Refurbishing existing detectors</u>: **important for SX studies today**
  - Launching R&D and discussing funding: **important in the longer term, collaboration is encouraged**

Spill quality R&D opportunities at CERN

- NA experimental requirements limits the application of most RF techniques (even up to 800 MHz)
- No SPS parallel machine time for SX studies:
  - Limited R&D time on the machine and shared during dedicated time with other users, e.g. LHC studies
- PS and East Area provide us with a unique opportunity for R&D:
  - Physics users would benefit from spill quality improvements
  - Lower beam power eases machine protection concerns
  - Multiple and flexible RF systems and an active RF team
  - Irradiation users (IRRAD and CHARM) are blind at RF time scales:
    - Opportunity to carry out RF studies with limited perturbation to the operation
- East Area Consolidation project is nearing completion:
  - **A refurbished spill quality monitor is now ready for tests!**
  - Investigating R&D cycle in parallel to operation using new beam dump

Recent R&D achievements (i)

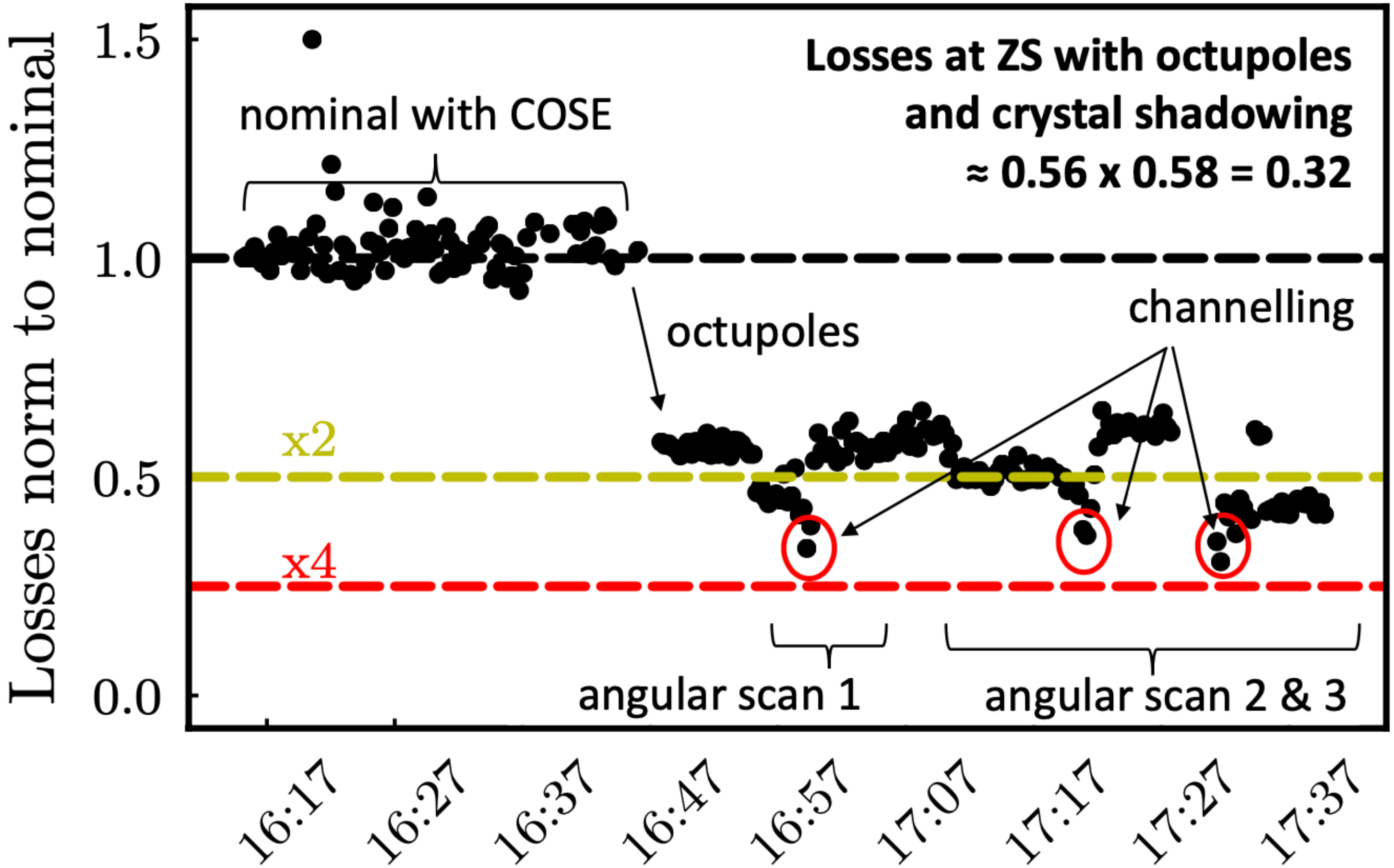
Loss reduction topics

Possible IFAST.REX collaboration topics

Topic	Result	Challenges	Next steps
Extraction efficiency measurements [1]	~3.5% inefficiency, about x3 more than expected!	Absolute intensity and BLM calibration issues	Longitudinal BLM (fibre optic device in development): prototype device installed, for online efficiency measurements
FLUKA [2]	Modelled entire LSS, BLM response (simulated vs. measured) corrborates poor extraction efficiency	Modelling misalignment, uncertainty on BLM detector response, CPU intensive	Benchmarking with multi-turn simulations
Passive diffuser (upstream wire array) [3]	~15 – 20% loss reduction, first measurement of electrostatic septum thickness	Wire array must be tailored to thickness of electrostatic septa: we underestimated septum thickness	Investigation has found warping of anode support of septa (~ 500 um vs. 60 um): looking at mechanical design options, possible modifications in next septa
Crystal active diffuser [4] (shadowing)	~ 45% loss reduction with prototype	Limited by single-pass channelling efficiency	Optimised system to be installed end 2021, investigating multi-crystal arrays aligned to volume reflection (high efficiency)
Octupoles [5] (phase space folding)	~ 40% loss reduction	Large emittance in plane of extraction	Transport and split octupole beam (high losses on first attempt)
Constant Optics Slow Extraction [6]	Stabilise separatrix orientation of extracted beam at septum	High-level control system needed (LSA): hundreds and thousands of linked parameters	Successfully tested at MedAustron [7 and D. Prokopovich's talk later today] LSA control of SX to be implemented at PS

Last beam tests in 2018…

- Final 400 GeV p+ SPS beam tests of Run 2 on 1 November 2018:



Recent R&D achievements (ii)

Loss reduction topics

Possible IFAST.REX collaboration topics

Topic	Result	Challenges	Next steps
Automatic septum alignment [8]	Powell based optimiser aligned < 1 hour, vs 8 hours for a human!	Many degrees of freedom: 5 septum tanks (2 motors each) + girder	Deploy an operational application, build a data driven model and test reinforcement learning
Induced radioactivity studies [9]	FLUKA model used to quantify benefits of using low-Z material: e.g. Al or Ti vacuum tanks, anode supports and wires	Poor thermal conductivity or Ti anode wires Manufacturing Al flanges Mechanical striaghtness of anodes	Prototype low-Z electrostatic septa: aim for installation in 5 years Improved remote handling
Carbon nanotube wires [10]	HV tests undertaken, modest fields of a few MV/m achieved	Fragile, carbon pollution detected after sparking, difficult to condition, unreliable HV performance	Rather invest effort in alternatives, e.g. Ti, graphene foils
Modelling of induced radioactivation [11]	Empirical model to predict induced radioactivity and cooldown times based on future proton flux	Uncertainty on ~10%	Potential for a future operational application
Massless septum [12]	Use the fringe field of a dipole to reduce beam density at septum: ~50% loss reduction	Non-linearities & phase space folding at high sextupole strengths	Potential for follow-up and application to lower energy machines
Mini-ZS [13]	Small upstream high field septum (like an active diffuser), conventional tecnnology, up to 50% loss reduction		Potential for application in NA transfer lines to improve splitting efficiency

Recent R&D achievements (iii)

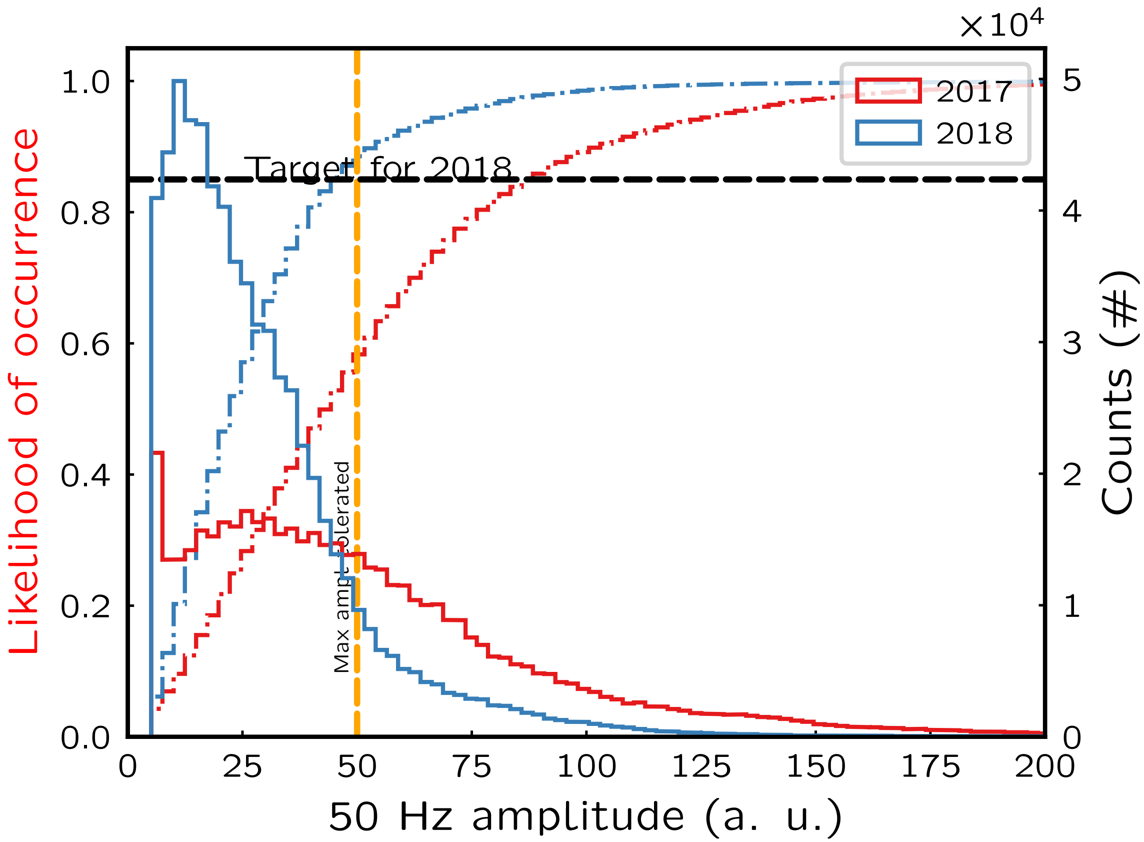
Spill quality (**F. Velotti** to present more details)

Possible IFAST.REX collaboration topics

Topic	Result	Challenges	Next steps
Understanding irreproducbility [14]	Magnetic measurements combined with MADX explained relative tune variations of ~7×10^{-3} degrading the spill quality	Regular changes to super-cycle and hysteresis effects, e.g. LHC / AWAKE	Application of machine learning to predict tune changes that need applying as supercycle is changed
Feed-forward spill control	SW application measures ripple on extracted spill (50, 100, 150 Hz) and applies correction	Unknown source of jitter on phase relative (might be on measurement device)	Apply correction on all circuits (via COSE) instead of dedicated servo quadrupoles
SPS burst extraction (pulsed horn neutrino beams, ENUBET) [15,16]	Capable of controlling SPS tune to mulitple burst extraction with ~ ms pulses at 10 Hz	Limited by beam's low pass filter effect (long transit time at SPS)	Try with (i) half integer extraction (ii) combine with octupoles and higher sextupole strength
Transfer function characterisation [17]	Dedicated measurements injecting noise on main circuits understood with beam simulations	Power converter control interfering with measurements	Exploit simulation model to optimise slow extraction parameters for less sensitivity to power converter ripple To be carried out at PS
High frequency ripple [18]	Measurements of 200 MHz evolution (debunching during spill)	SPS experiments/users sensitive to ripple on almost all timescales, even up to 200 MHz	Develop operational fast spill detectors with higher bandwidth

Improvements at SPS in 2018…

- Regular monitoring and correction of the n x 50 Hz harmonic component:



Recent R&D achievements (iv)

Simulations tools

Possible IFAST.REX collaboration topics

<table>
<tr><th>Topic</th><th>Result</th><th>Challenges</th><th>Next steps</th></tr>
<tr><td>MADX thin tracking and PTC</td><td>Impressive benchmarking with non-linear beam studies, e.g. octupole extraction</td><td>Slow, poor interface for custom beam interactions (with matter, special devices, e.g. crystals, septa, RF exciters etc)</td><td>MADX is our reference tool…</td></tr>
<tr><td>maptrack [19,20]</td><td>Non-linear maps extracted from PTC at arbitrary order, tracking in python with interface to custom modules, e.g. pycollimate</td><td>Careful generation of maps (# and order) needed with benchmarking to PTC in every application</td><td rowspan="3">Open LGPL license, encourage collaboration and increase modules/functionality:

Have a chat with Francesco Velotti!

Introduction of custom RF elements:
• RF noise exciters (transverse/longitudinal)
• Empty bucket channeling
• Barrier buckets

Exploit model to optimise machine parameters

Semi-analytic approach being investigated</td></tr>
<tr><td>pycollimate [21]</td><td>Interaction of beam with custom elements (matter, crystals, benchmarked to FLUKA, benchmarked to beam measurements</td><td>Simulation time a good compromise vs. FLUKA</td></tr>
<tr><td>Henon maps [17] (longitudinal)</td><td>Success in modelling measured transfer functions in SPS and MedAustron</td><td>Fast for low frequency studies, particle number becomes challenging as resolution moves to ~ MHz</td></tr>
</table>

Spill quality instrumentation

Topic	Result	Challenges	Next steps
Slow extracted beam intensity measurements [22]	Dedicated tests showed wide variation (~ 50%) in measured intensity on SEM type devices Electronics consolidated for time dependence during spill ~ 10 Hz	Known issues (ageing, etc) inc. with vacuum quality etc. Presently no easy way to calibrate our SPS intensity monitors in NA	Considering methods for frequent calibration of SEMs: no easy solution Considering other monitors (BCT, CCC)
Cherenkov detector fast spill monitor [19]	Quartz bar coupled to PMT Spill measured on a wide range of timescale (Hz to 200 MHz) sampling at 2 GHz	Further development needed	Successful collaboration beween CERN & UA9. Build towards the development of an operational device
SPS OTR monitor	Refurbished OTR screen coupled to PMT	Performance to be understood with beam this year	
PS scintillator refurbishment	Refurbished gas (N2) scintillator, two detectors in coincidence, new acquisition chain, PMT up to ~ MHz	Performance to be understood with beam this year	
Beam loss measurements for temporal spill quality measurements:			
Diamond BLM's	Installed detectors in SPS LSS2 Expect up to to see 200 MHz	Location of detector / saturation, etc.	To be tested this year and DAQ
LHC BLM's at SPS	Good temporal resolution up to 20 us: could see the impact of COSE!	Working on pulsed cycles, important for beam loss studies	Integrate software in SPS control system

CERN-IFAST.REX R&D threads

Topic	Framework	Next steps	Resources
Absolute DC beam intensity measurements	**Operation:** (i) presently transimission to targets is not well understood	Decide on future approach: calibration options for SEM or current transformer	NA Consolidation project approved and could support development
RF techniques and spill quality	**PBC:** (i) BDF: bunched proton beams with variable spacing (ii) eSPS: very low extraction rates in presence of synchroton radiation	Revive old RF techniques at the PS before moving on to newer techniques (inc. barrier buckets) and to SPS: Benchmark measurements/simulations	CERN Doctoral student started at Oxford, arriving at CERN on 1 April
Code development	Continued exploitation development of simulation tools for all studies	(i) Exploit model to optimise slow extraction parameters for spill quality (ii) Online prediction of current variation on the spill (feed-forward)	Beam time available for benchmarking model to measurements **Exploit PS!**
Fast longitudinal spill monitor	**Operation:** (i) presently limited in control room (bandwith 2.5 kHz) (ii) Rely on dedicated studies/info from experimental users **PBC:** (i) Required for future spill quality studies	(i) Refurbished SPS OTR monitor (ii) Refurbished PS gas scintillator Other options: (i) Response from SEM’s (ii) Investigating future of CpFM (iii) Diamond detectors	Review performance of refurbished devices with beam decision to be made on development of > MHz detector this year

Slow Extraction Workshop Series

- Last 5 years of SX WS series has generated a small but active community in the field: **we should keep it alive!**
- Next Workshop was planned in October this year in Tsukuba KEK-JPARC…
  - Remote option being considered, as well as an April 2022 date

References

[1] M.A. Fraser et al., *Slow Extraction Efficiency Measurements at the CERN SPS,* IPAC 2018, #TUPAF054

[2] L. Esposito and D. Bjorkman, *Establishing a FLUKA model for slow extraction in LSS2,* presented at the SLAWG meeting, CERN – 24 Jan. 2018.

[3] B. Goddard et al, Reduction of 400 GeV/c slow extraction beam loss with a wire diffuser at the CERN Super Proton Synchrotron, Phys. Rev. Accel. Beams **23**, 023501 – 7 Feb. 2020

[4] F.M. Velotti et al., *Septum shadowing by means of a bent crystal to reduce slow extraction beam loss,* Phys. Rev. Accel. Beams 22, 093502 – 27 Sept. 2019

[5] M.A. Fraser, Demonstration of slow extraction loss reduction with the application of octupoles at the CERN Super Proton Synchrotron, Phys. Rev. Accel. Beams 22, 123501 – 11 Dec. 2019

[6] V. Kain et al., *Resonant slow extraction with constant optics for improved separatrix control at the extraction septum,* Phys. Rev. Accel. Beams 22, 101001 – 9 Oct. 2019

[7] P. Arrutia, Master Thesis, Optimisation of Slow Extraction and Beam Delivery from Synchrotrons, Royal Holloway, University of London, 2020 – CERN-THESIS-2020-259

[8] S. Hirlaender et al., Automatisation of the SPS ElectroStatic Septa Alignment, IPAC 2019, #THPRB080

[9] D. Björkman et al., Alternative Material Choices to Reduce Activation of Extraction Equipment, IPAC 2019, #WEPMP024

[10] J. Borburgh, *Carbon Nanotube ES wire Studies at CERN,* presented at ICFA Mini-Workshop on Slow Extraction, FNAL, 22-24 July 2019

[11] M. A. Fraser, *Activation monitoring and prediction models,* presented at 2017 ICFA Mini-Workshop on Slow Extraction, CERN, 9 - 11 Nov 2017

[12] K. Brunner *et al.*, *Use of a Massless Septum to Increase Slow-Extraction Efficiency*, IPAC 2018, #TUPAF061

[13] D. Veres, *Summary of Mini-ZS project*, presented at the SLAWG meeting, CERN – 28 Aug. 2019.

[14] F.M. Velotti et al., Characterisation of SPS Slow Extraction Spill Quality Degradation, IPAC 2019, #WEPMP034

[15] M. Pari et al., Model and Measurements of CERN-SPS Slow Extraction Spill Re-Shaping - the Burst Mode Slow Extraction, IPAC 2019, #WEPMP035

[16] [18] M. Pari, PhD thesis, Study and development of SPS slow extraction schemes and focusing of secondary particles for the ENUBET monitored neutrino beam, University of Padova, submitted 2020.

[17] M. Pari et al., Characterization of the slow extraction frequency response, submitted to PRAB on 11 December 2020

[18] F. Addesa, PhD thesis, *In-vacuum Cherenkov light detectors for crystal-assisted beam manipulations*, University of Rome, Sept. 2018, CERN-THESIS-2018-363

[19] maptrack: https://gitlab.cern.ch/abt-optics-and-code-repository/simulation-codes/maptrack

[20] F.M. Velotti et al., *Speeding up Numerical Simulations with PTC Maps at Arbitrary Order,* presented at 2019 ICFA Mini-Workshop on Slow Extraction, FNAL, 22-24 July 2019

[21] pycollimate: https://gitlab.cern.ch/fvelotti/pycollimate

[22] F. Roncarolo, *Investigation of BSI calibrations,* presented at the SLAWG meeting, CERN – 21 Feb. 2018.

General references material

- SX Workshops:
  - 2016: https://indico.gsi.de/event/4496
  - 2017: https://indico.cern.ch/event/639766/
  - 2019: https://indico.fnal.gov/event/20260
- SPS Loss and Activation Working Group meetings and minutes are a useful resource:
  - SLAWG: https://indico.cern.ch/category/7887/
- SPS Crystal Assisted Slow Extraction WG
  - SPS-CASE WG: https://indico.cern.ch/category/8556/