CERN

Requirements and achievements at CERN PS and SPS

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See the recent Slow Extraction WS for details:

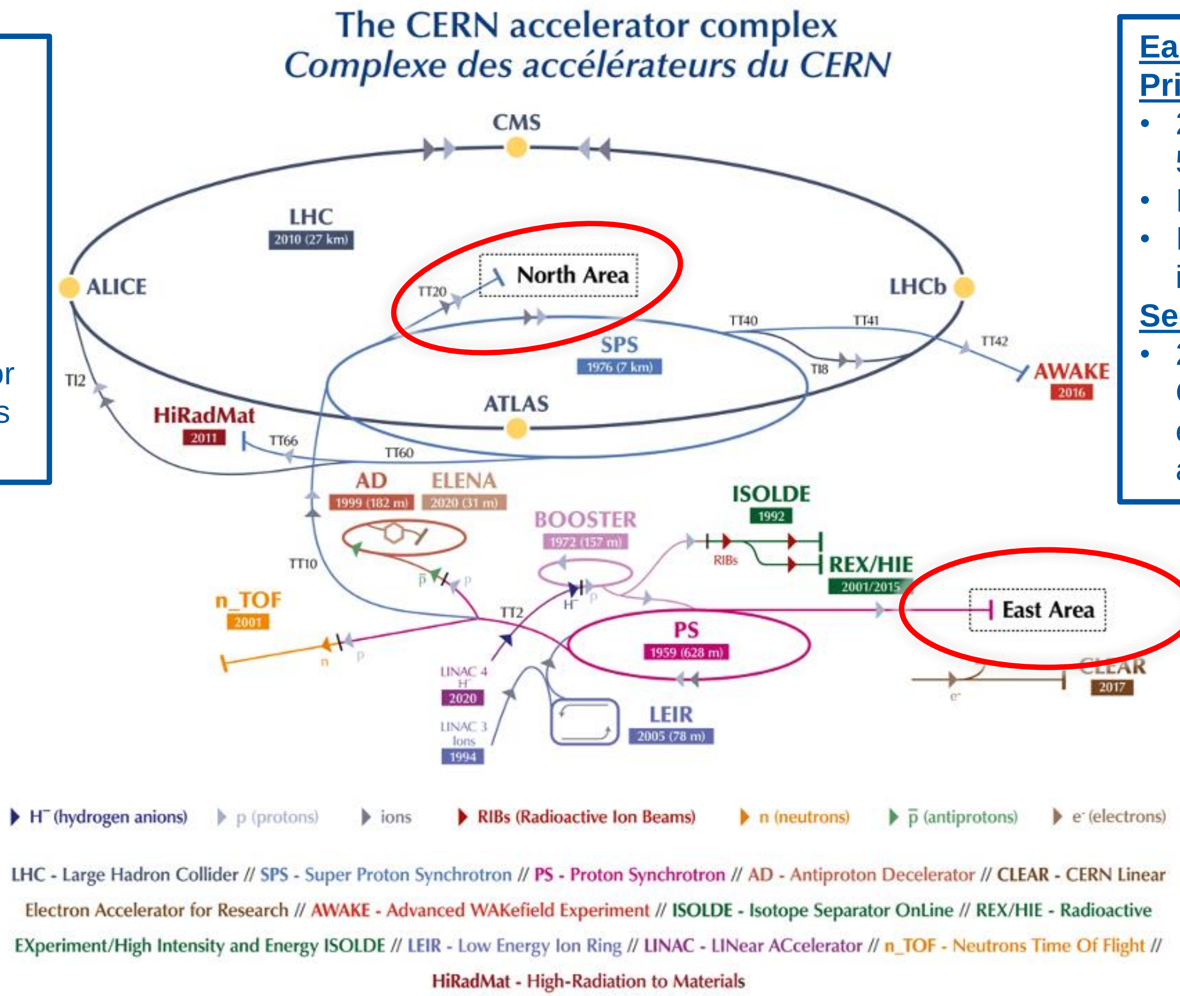
Talk Outline

- Brief overview of CERN’s SX systems
- PBC at CERN
- Recent slow extraction R&D achievements
  - Beam loss reduction
  - Machine stability, reproducibility and spill quality
  - Beam dynamics simulation tools
- Collaboration opportunities
- 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 < 500 Hz)	60%	95 %

PBC requirements @ 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 with factor x4-5 needed
  - **Focus moving now to spill quality and time structure (bunched beams)**
- In 2021 we (SY-ABT) started exploited the CERN PS for studies support in part by PBC.

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) in SPS Implementation in the PS
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] LSA control of SX to be implemented at PS

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	Operational application deployed
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

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/SPS with RF (4D)
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

Recent R&D achievements (iv)

Simulations tools

Possible IFAST.REX collaboration topics

Topic	Result	Challenges	Next steps
MADX thin tracking and PTC	Impressive benchmarking with non-linear beam studies, e.g. octupole extraction	Slow, poor interface for custom beam interactions (with matter, special devices, e.g. crystals, septa, RF exciters etc)	MADX is our reference tool…
maptrack [19,20]	Non-linear maps extracted from PTC at arbitrary order, tracking in python with interface to custom modules, e.g. pycollimate	Careful generation of maps (# and order) needed with benchmarking to PTC in every application	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
pycollimate [21]	Interaction of beam with custom elements (matter, crystals, benchmarked to FLUKA, benchmarked to beam measurements	Simulation time a good compromise vs. FLUKA	
Henon maps [17] (longitudinal)	Success in modelling measured transfer functions in SPS and MedAustron	Fast for low frequency studies, particle number becomes challenging as resolution moves to ~ MHz	

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	Good performance up to ~ 10 kHz	
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 collaboration opportunities

- Simulation code development in WP3
- Knowledge exchange / forum
- PS machine is "available” for benchmarking with measurements:
  - Parallel operation to physics (new beam dump option)
  - Flexible RF systems & improving spill quality monitoring
- Topics need to be focused on spill quality (but beam loss also):
  - Empty bucket channelling
  - Effect of RF noise techniques on spill transfer functions inc. longitudinal and transverse RF
  - Ultra slow extraction with RF noise (low, stable extr. rates)
- Machine stability with feed-forward/feed-back techniques
  - Hysteresis modelling (machine learning) and optimisation
- Development of spill quality instrumentation in WP4
- Let’s discuss any other opportunities

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
  - 2022: https://conference-indico.kek.jp/event/163/overview
- 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/