CERN

SPS: present and future challenges

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with contributions from B. Balhan, H. Bartosik, T. Bohl, J. Borburgh, K. Cornelis, L. Gatignon, B. Goddard, M. Gyr, V. Kain, P. Petrov, F. Velotti, H. Vincke

Outline

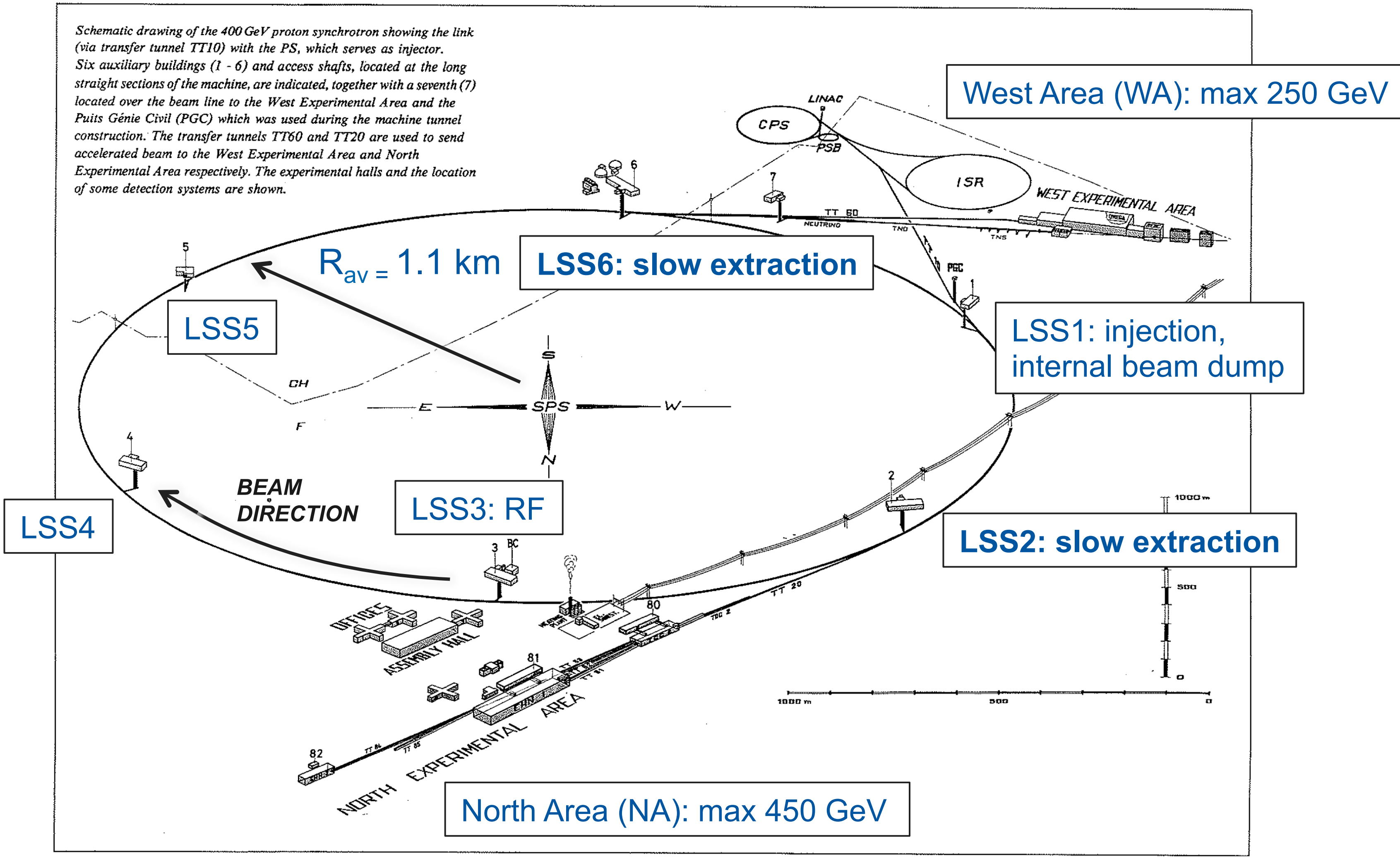
- Introduction to SPS
  - A (very) brief history of slow-extraction
- Present challenges
  - Proton cycle: high intensities, activation, maintenance, multi-cycling, reproducibility, stability…
- Future challenges
  - A (very) brief look to the future
- Summary

A brief history of SPS

- 1976: 400 GeV **p+** beams (originally specified 300 GeV)
  …a Fixed Target (FT) facility by design!
- 1981 - 1993: **p^+/p^-** collider at 270 GeV (later 310 GeV)
- 1986: first **heavy ions** accelerated for FT
- 1989: LEP injector (20 GeV **e^-/e^+)**
- 1994 - 1998: WANF neutrino facility (450 GeV **p^+**, slow half-integer extraction, spills of 6 – 10 ms, 70E18 p.o.t. in 4 yrs)
- 2006 - 2012: CNGS neutrino facility (400 GeV **p^+**, fast extraction, 180E18 p.o.t. in 5 yrs)
- 2008: LHC injector (450 GeV **p^+**)
- Today: NA FT physics (**heavy ions** and 400 GeV **p^+)**, HIRADMAT, AWAKE and LHC **(heavy ions** and 450 GeV **p^+**)

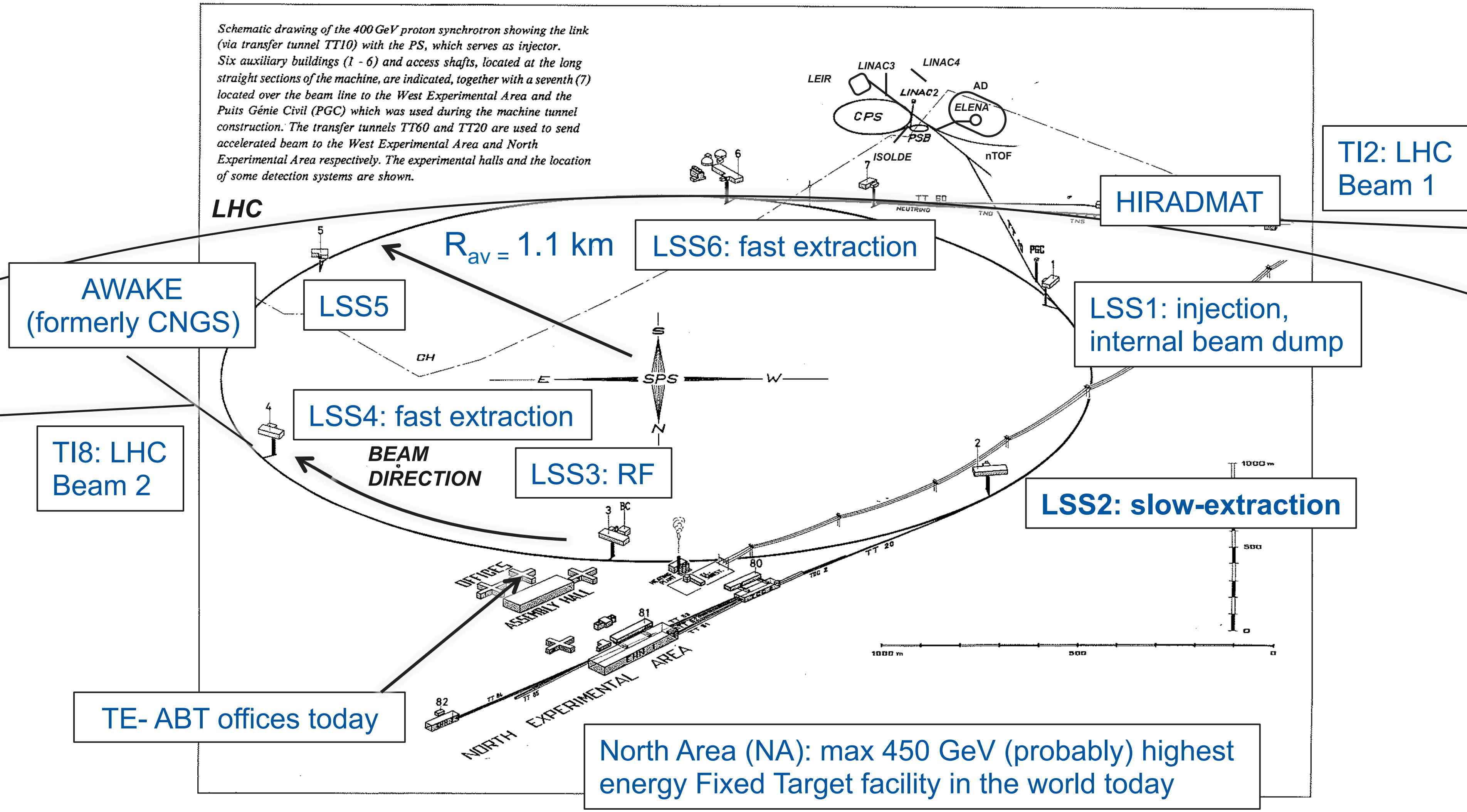
~ 40 years of Fixed Target physics

CERN in 1976



[1] J.B. Adams, The CERN 400 GeV Proton Synchrotron, 1977

CERN in 2016



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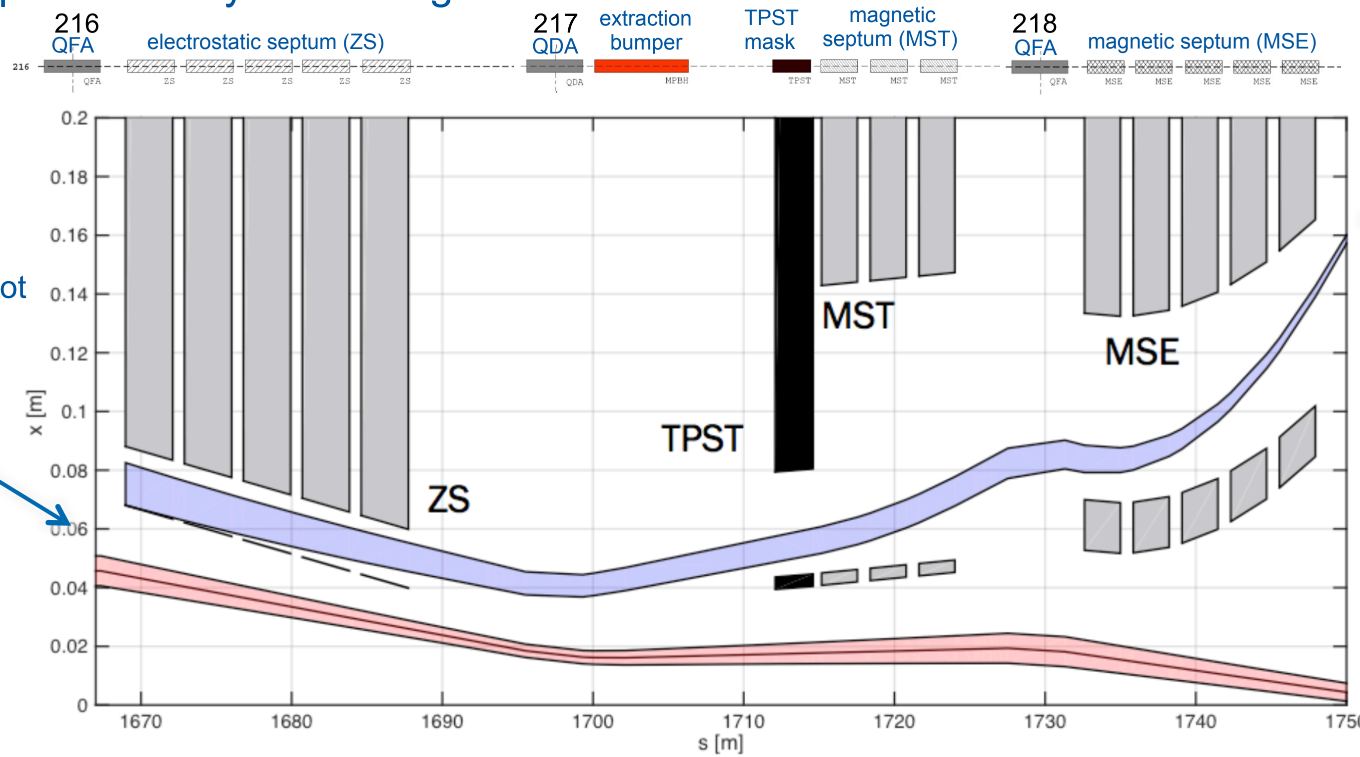
Slow extraction at SPS

- Extraction geometry designed in 1970's and largely unchanged:
  - Three septa: electrostatic (ZS) and two magnetic septa (MST/MSE) and 5 "bumpers"
  - Extraction hardware has slowly evolved over 40 years, LSS2. state-of-the art to be presented by J. Borburgh

Hardt condition not fulfilled:
D ~ 0.1 m
D' ~ 6 mrad



To TT20 and NA

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

A brief history of SE at SPS

- From 1976: third-integer slow extraction to WA at 200 GeV (RF on) before acceleration to 400 GeV and extraction to WA or NA
  - A very fruitful time for slow extraction research!

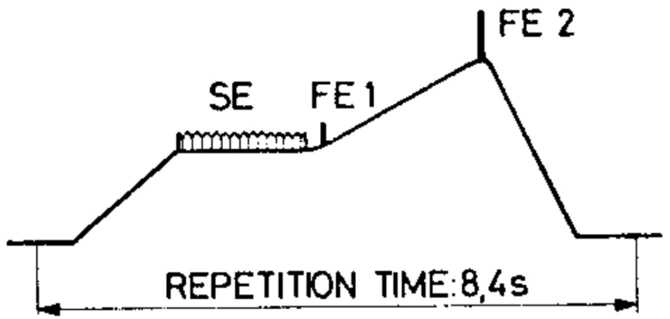
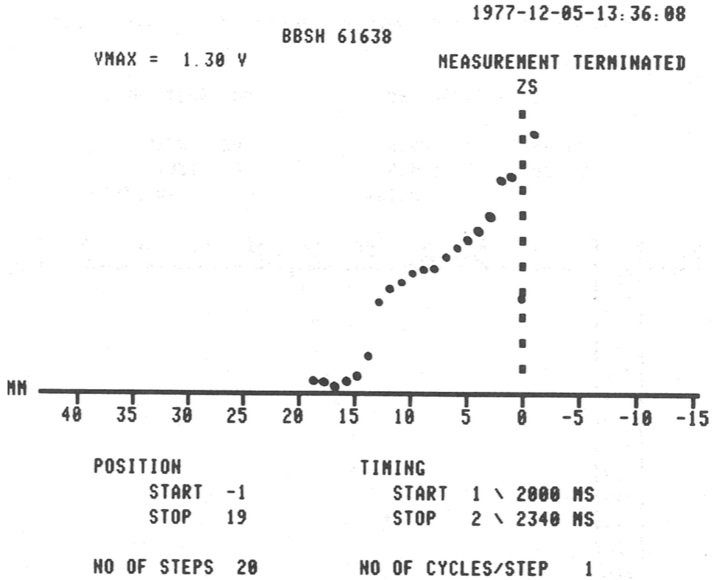


Fig. 2 Typical SPS cycle; SE = slow ejected beam at 200 GeV/c, FE1 and FE2 fast extracted beams at 208 and 400 GeV/c resp.

"the blow-up of emittance is an embarrassment… when the r.f. is kept on"

[2] M. Cornacchia, 1977



Beam profile at ZS (BBSH.61638) in LSS6 in 1977

Nominal septum gap width = 20 mm, spiral step ~ 15 mm

[2] M. Cornacchia, Third-integer slow-extraction with the rf on, 1977

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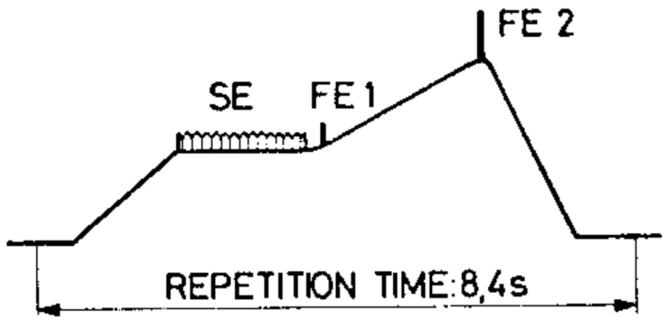

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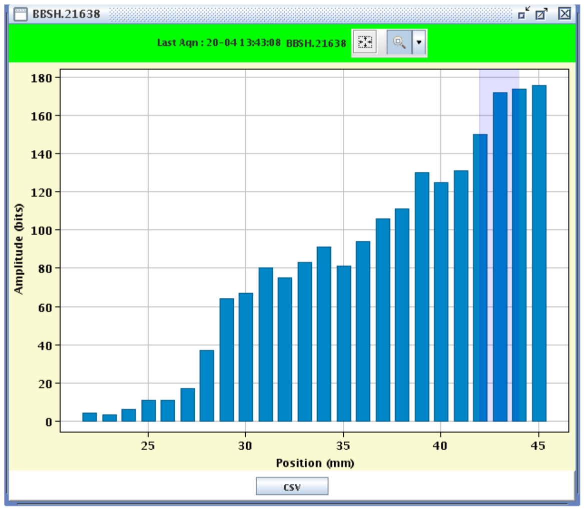

Beam profile at ZS (BBSH.21638) in LSS2 today

…spot the difference!

Nominal septum gap width = 20 mm, spiral step ~ 15 mm

[2] M. Cornacchia, Third-integer slow-extraction with the rf on, 1977

A brief history of SE at SPS

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- 1983: WA upgraded, tune-split introduced in QF circuits allowing simultaneous slow extraction to NA and WA at 450 GeV

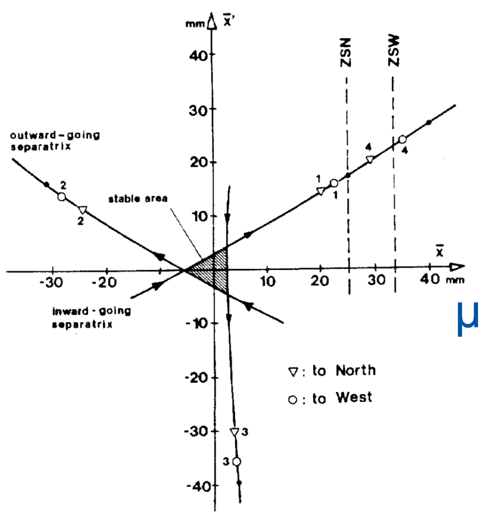

Fig. 1 - Normalized phase space locations of particles at the entrances of the ZS's during the last 3 turns before extraction.

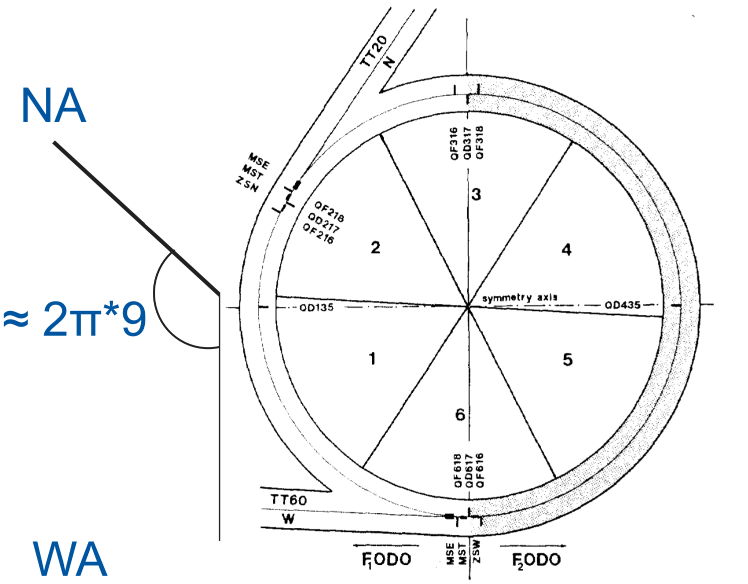

Fig. 2 - Layout of SPS with split horizontal tune

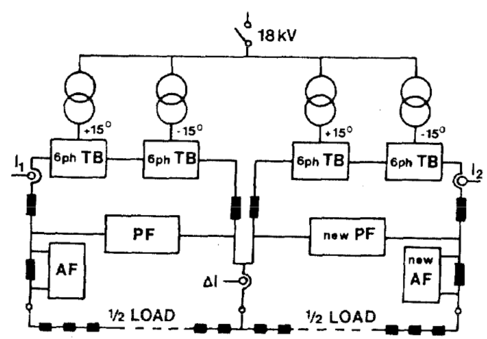

Fig. 3b - Modified SQF Power Supply

$\Delta I/I_{av} = 1.6\%$

[3] M. Gyr et al., Simultaneous slow resonant extractions from the SPS with horizontal tune-split, 1983

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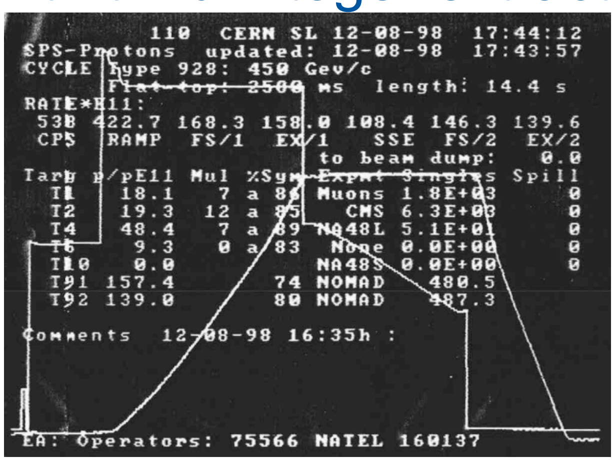
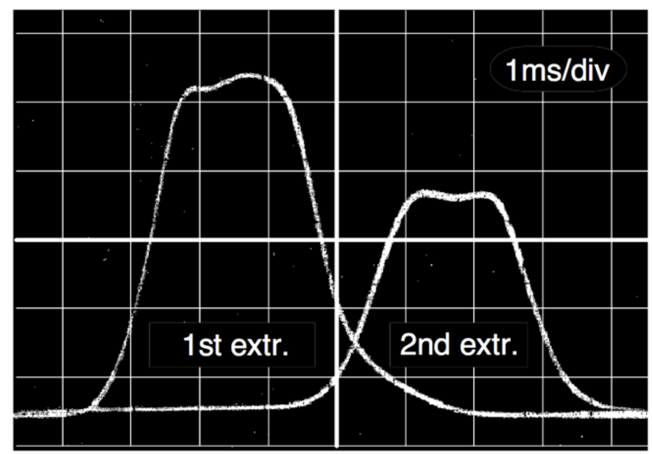


SPS Page 1: WANF sharing with NA



Fast-slow extractions (half-integer)

[4] M. Gyr, Half-integer Fast Resonant Extraction with Quasi Rectangular Spill, EPAC’92, 1992

SPS Page 1: WANF sharing with NA

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- 2016: Multi-Turn Extraction (MTE) non-linear resonant magnetic splitting in PS has been commissioned and operational today
  - transparent for slow extraction

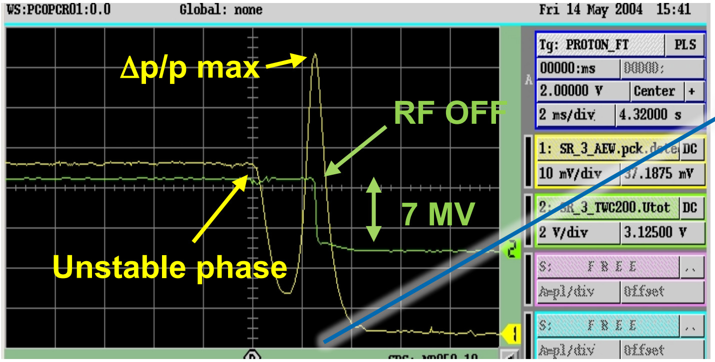
SPS FT proton cycle today

Parameter	Typical	Record	Comment
Extraction energy [GeV]	400	450	rms power limitation: 400 GeV for FT
Injection energy [GeV]	14	14	Transition crossed in SPS at ≈ 22.8 GeV
Bunch spacing [ns]	5	5	200 MHz RF system (h = 4620)
# bunches	4200	4200	10/11th of SPS filled with 2 PS batches (5 turns each, 1.2 s apart)
Bunch int. [p^+]	0.07E11	0.11E11	LHC ~1.1E11 p^+ per bunch
Extracted int. [p^+]	3 - 4E13	4.5E13	Slow-extracted (record ~5.3E13 for CNGS, FE)
Flat-top length [s]	4.8	9.6	Dependent on experiments' needs
Transmission [%]	94	98	Limited mainly at injection to SPS

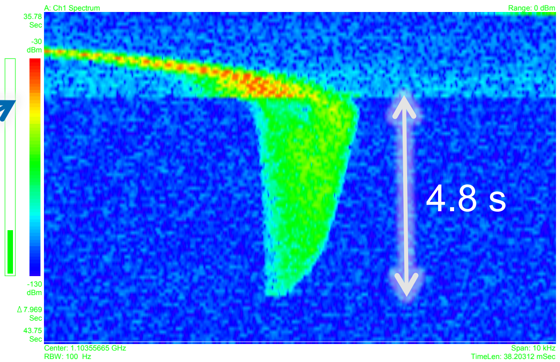
- Losses during the cycle are dominated by the injection losses (~ few %)
  - On-going optimisation for PS MTE
  - RF capture: beam arrives de-bunched and in two batches
  - Vertical aperture: injection closed orbit and tune critical, transverse damper, requesting smaller emittances/transverse shaving in PS booster

SPS slow extraction today

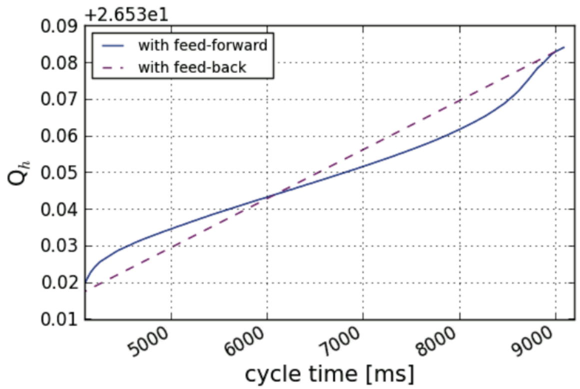
- At 400 GeV flat-top:
  - RF gymnastics to increase Δp/p (π-phase jump, rotation, off)
    - $\Delta p/p_{rms} \approx$ 2E-4 to 4E-4
  - Sextupoles increase chromaticity and thus tune spread ($\xi_{H\approx}$ -1, $Q'_H \approx$ -30)
  - Extraction sextupoles turn on, extraction bump on at ZS
  - Main quadrupole current ramped to sweep resonance (26.666…) through tune spread ΔQ ~ 0.06 (extracted beam momentum increases)



RF gymnastics
(π-phase jump, rotation, off)



Schottky waterfall 2016



Tune ramp: with feed-forward on main quadrupoles

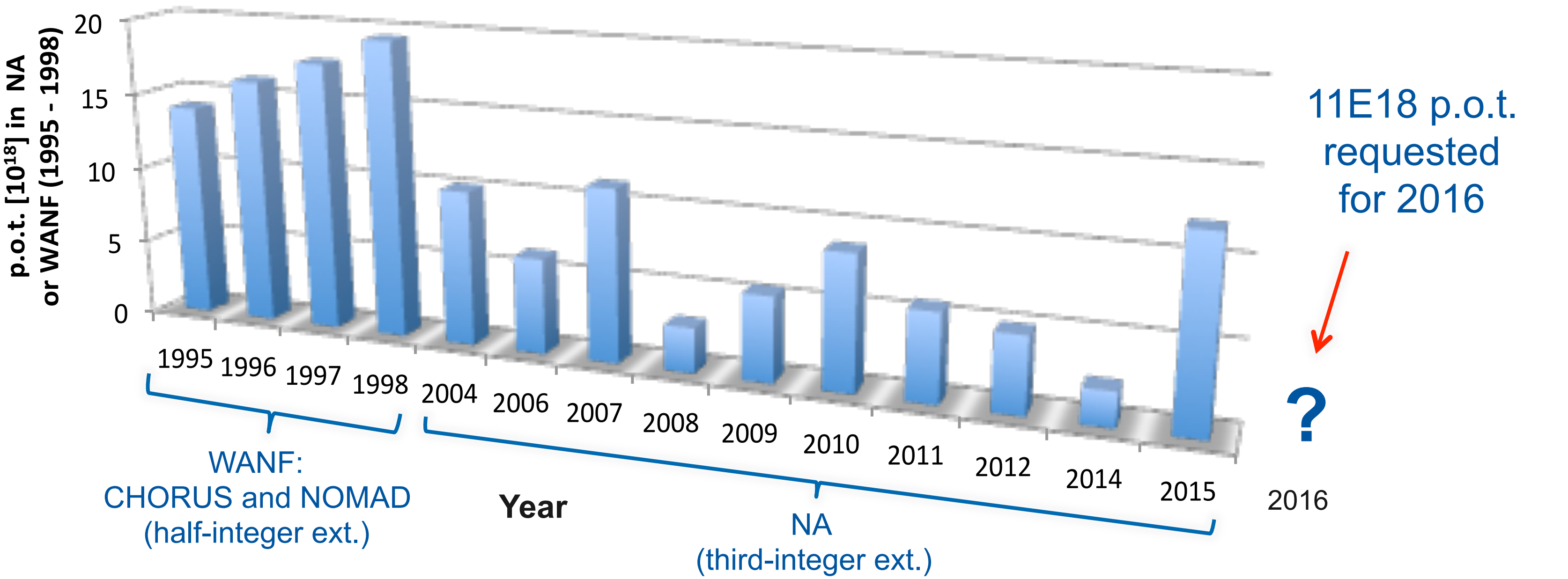
Present Challenges

- Regaining experience at CERN of operating at high intensities for high-energy Fixed Target physics:
  - Optimisation of extraction losses and induced activation
  - Monitoring of machine performance and interlocking
  - Improving machine stability and reproducibility (spill quality)
  - Maintenance of equipment in activated areas
- Doing all the above with a truly multi-cycling SPS
- ZS interacting with LHC beams, see talk by J. Borburgh
- Much needed and on-going consolidation of SPS (its not getting any younger!)

…looking to the future: machine development studies.

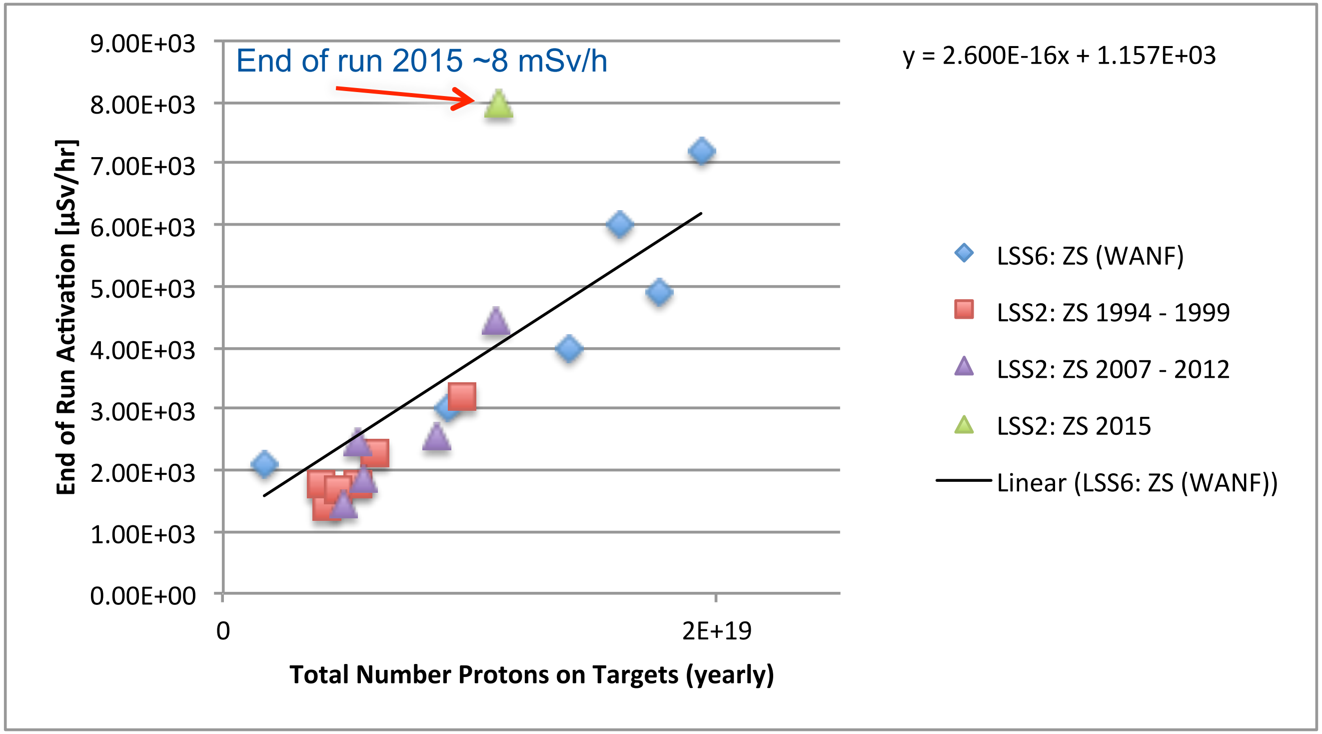
Intensity

- NA experimental physics programme is demanding the highest integrated intensities for about 17 years:



- Increased flux combined with increased losses per p^+ extracted led to increased activation levels in LSS2: similar to WANF era.
- SPS Losses and Activation Working Group (SLAWG) formed to investigate and follow-up the increase in activation during 2015.

RP activation surveys since 1994



Dose rate measured next to the ZS (**at ≈ 80 cm**) **30 hours** after SPS operation ceased.

- Linear relation just a rough rule-of-thumb: depends on extraction rate and efficiency of extraction in final days of the physics run, and the relative timing of the end of the FT and LHC physics runs.

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

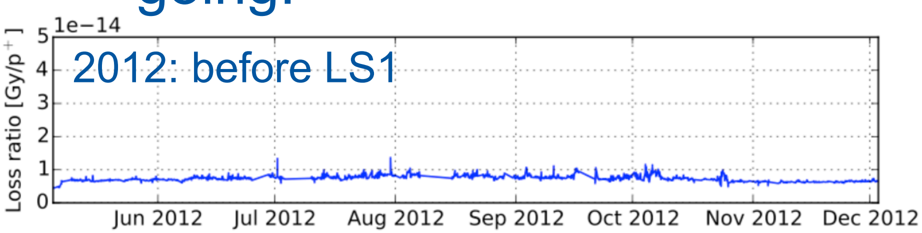
Year	BLM: ZS1 [Gy/10^{14} p^+]	BLM: ZS2 [Gy/10^{14} p^+]	BLM: ZS3 [Gy/10^{14} p^+]	BLM: ZS4 [Gy/10^{14} p^+]	BLM: ZS5 [Gy/10^{14} p^+]
2012	0.7	1.5	1.4	1.8	1.4
2014	1.7	n/a	2.4	2.9	1.8
2015	1.4	2.0	2.5	2.7	2.1
2016	0.7	1.9	2.2	2.1	1.7

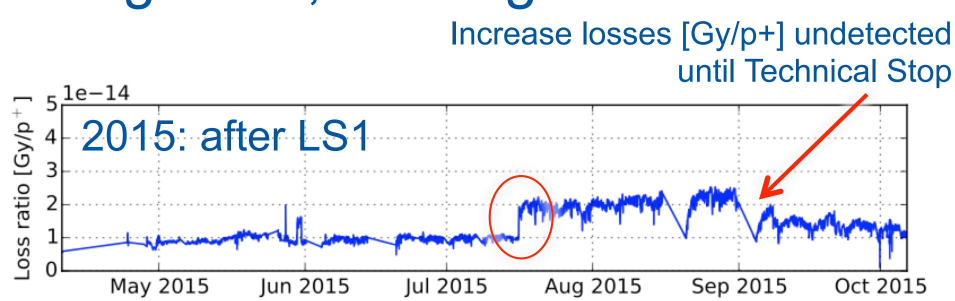
Recent normalised extraction losses (averaged over the year)

SPS QC monitoring application after first ZS alignment in 2016

Multi-cycling machine

- SPS has been multi-cycling since LEP injection during late 1980’s, however, only a single super-cycle was played.
- Since LS1 the SPS has become a truly multi-cycling machine:
  - Multiple FT cycles requested per super-cycle to satisfy experiments
  - More frequent super-cycle changes to facilitate LHC filling, AWAKE, HIRADMAT, MD cycles and parallel scrubbing
  - Dynamic economy mode now in operation (if no beam detected, magnets don’t ramp, RF doesn’t pulse) saving on the order of 1 M€ in 2015
- Stability of extraction losses has degraded, investigations on-going:

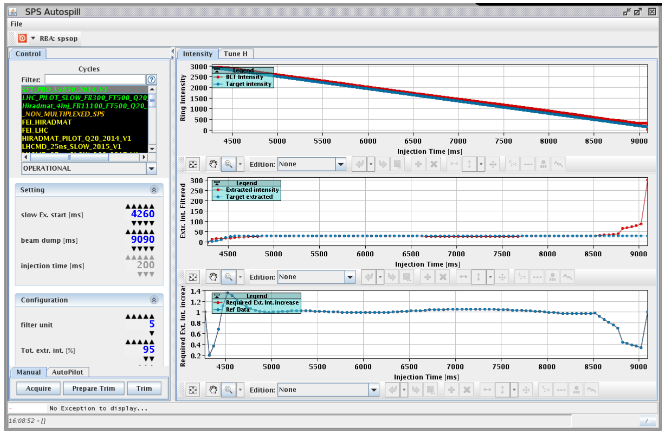




Normalised extraction losses per cycle measured next to first ZS tank
(not compensated for intensity dumped at end of spill)

Extracted trajectory stability

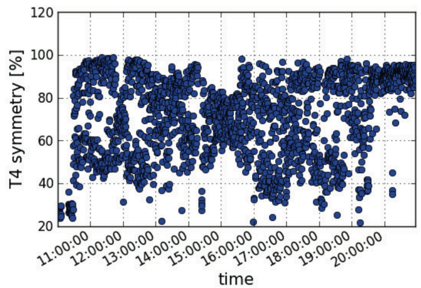
- Servo quad feedback with intensity measured in extraction line disconnected to improve trajectory stability in transfer line:
  - Shot-to-shot orbit variations amplified by servo quad
  - Feedback sensitive to cycle-to-cycle intensity variations
  - Small dimension of NA62 target in 2015 sensitive to steering errors
- Instead, feed-forward on current in main quadrupole (QF) circuit using *Autospill* [1] application:



Autospill application

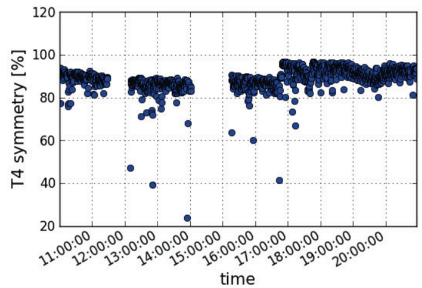
Symmetry measured on T4 target:

servo feedback:



1 Dec 2014

SMQ feed-forward:



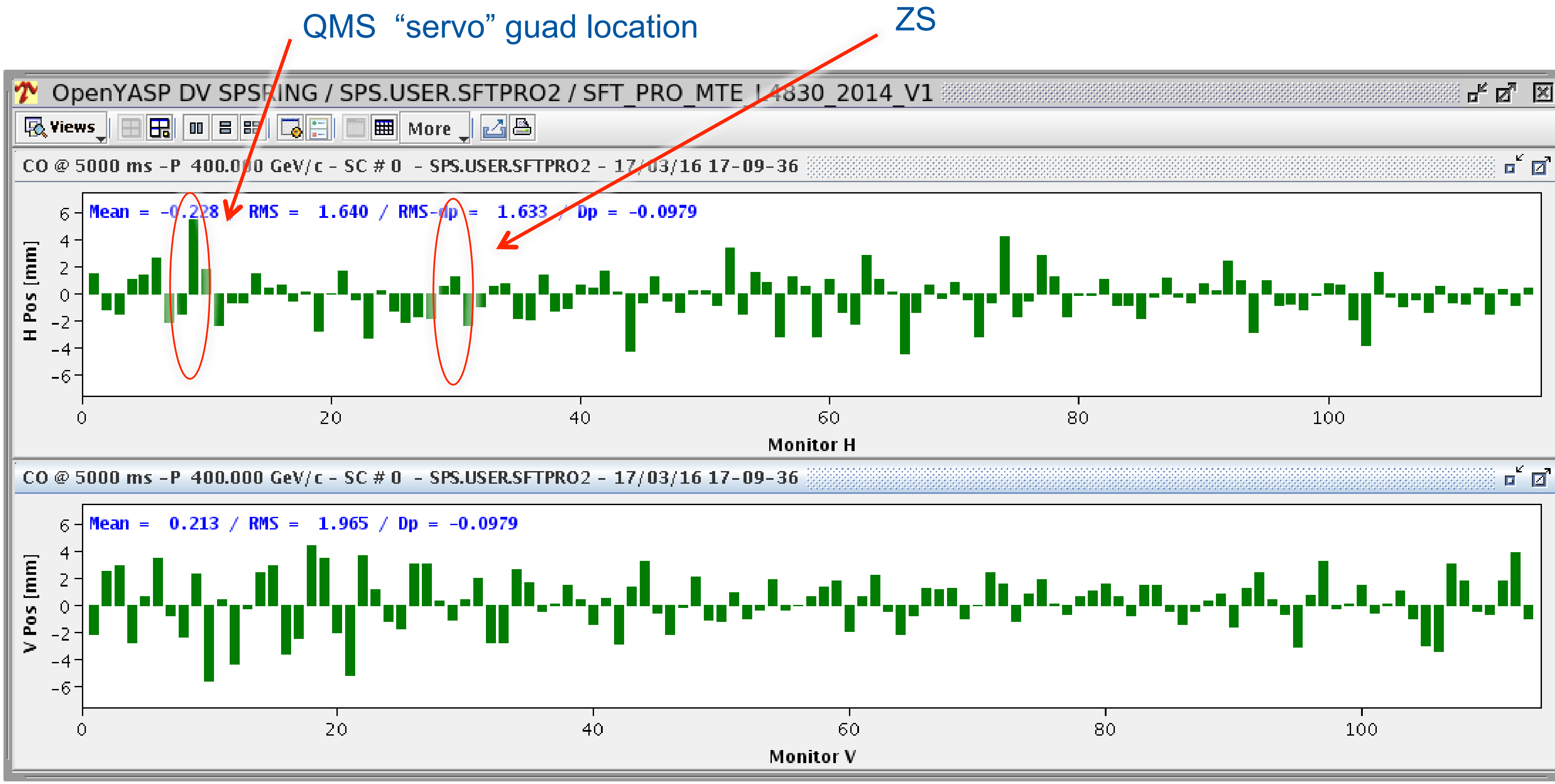
1 Oct 2015

Symmetry (at target): 100% = centred

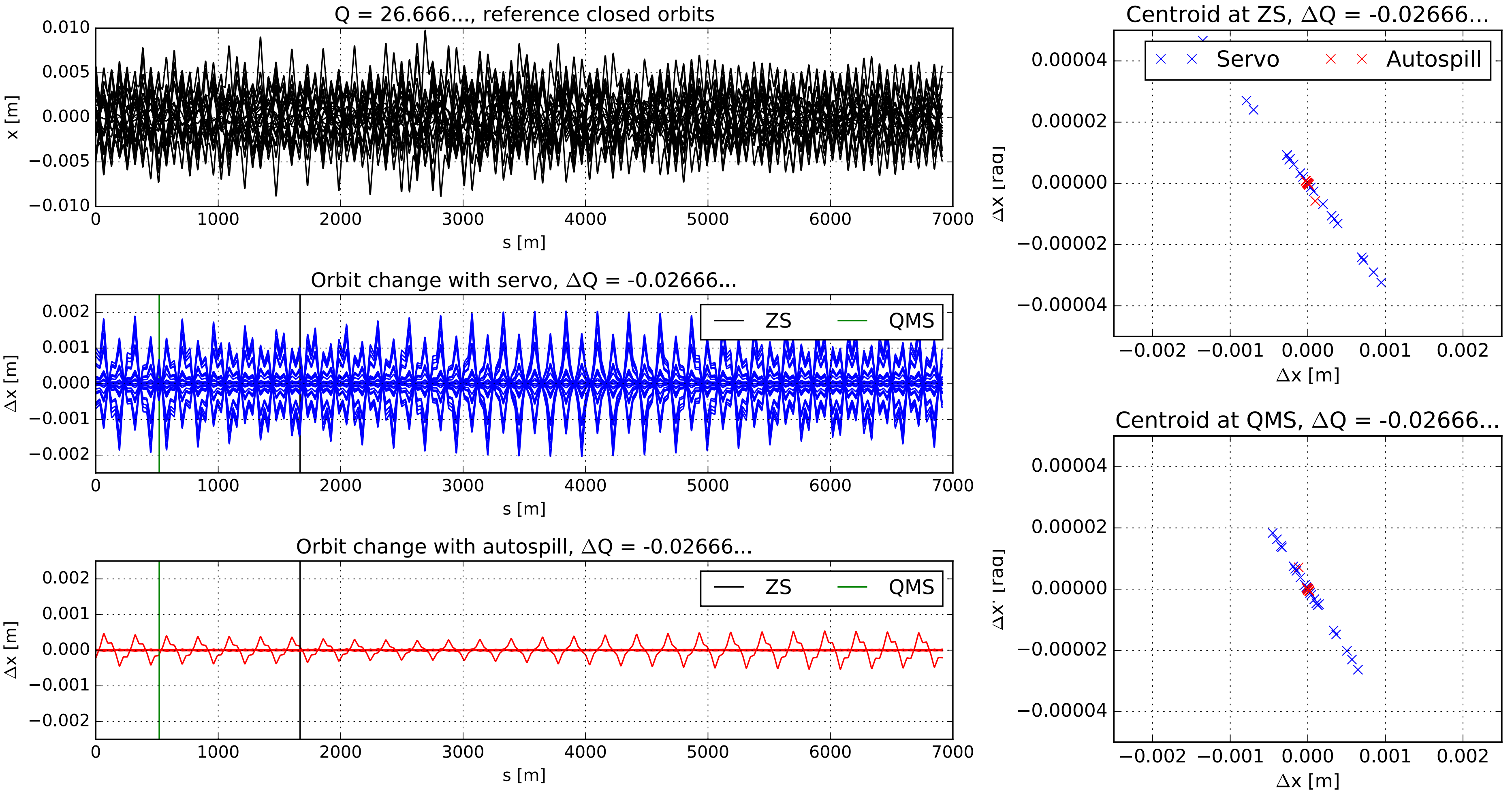
[5] V. Kain et al., New Spill Control for the Slow Extraction in the Multi-Cycling SPS, IPAC'16, 2016

SPS FT closed orbit at 400 GeV

- After beam-based alignment…

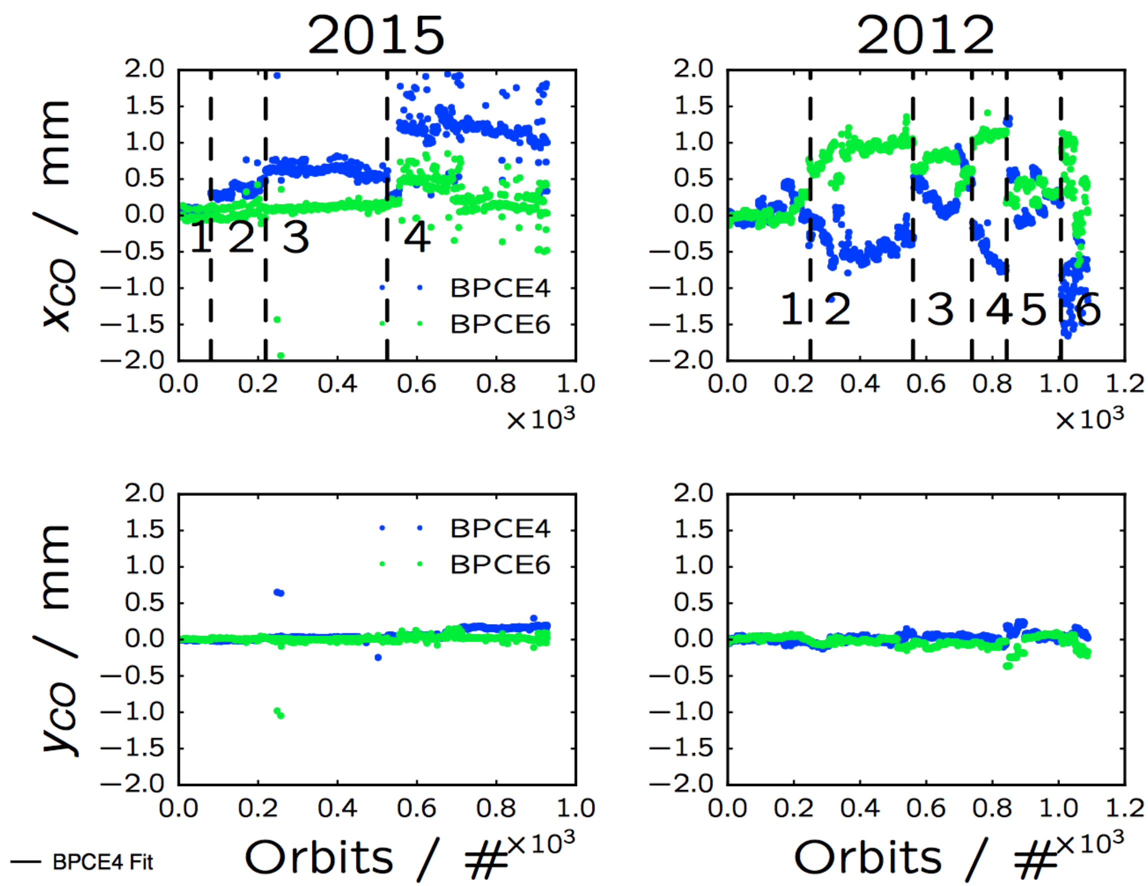


Orbit stability: servo quad (QMS, feed-back) vs. *Autospill* (feed-forward)



SPS orbit stability (LHC before extraction 450 GeV)

- Drifts of ~ mm observed over months (July to October 2015)



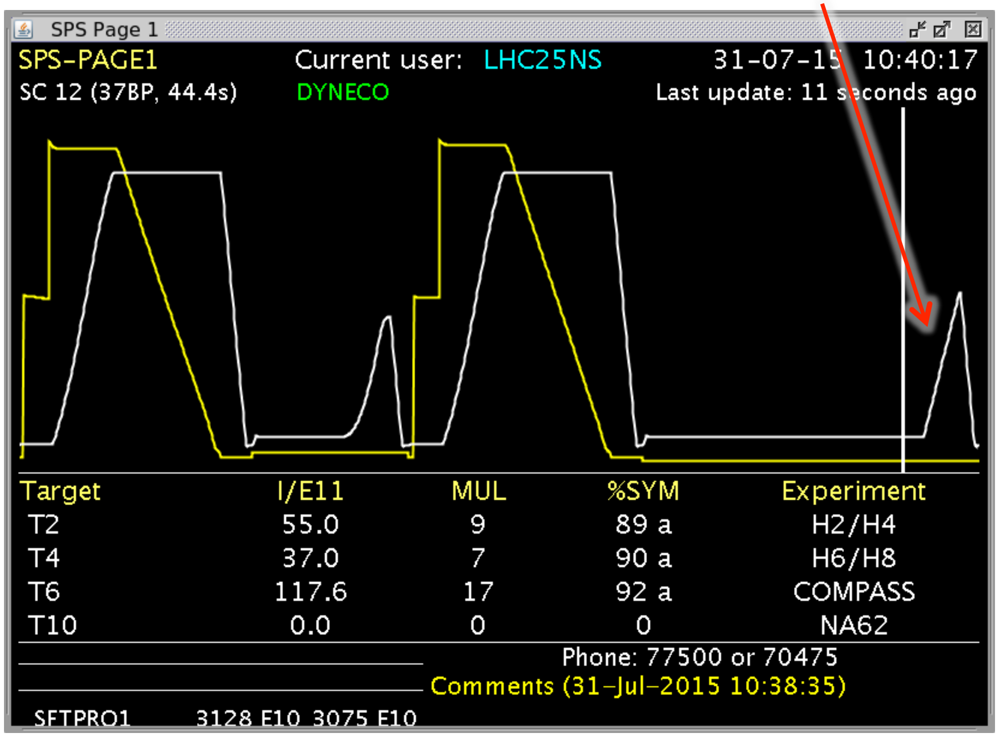
[5] F. Velotti et al., SPS Orbit Stability Analysis, MSWG meeting, 27 May 2016

Spill stability (1)

- *Autospill* has linearised the spill rate without perturbing the beam trajectory in the extraction line, and allows control of the ramp up and ramp down of the spill intensity:

e.g. dynamic economy, pulse to keep magnetic history

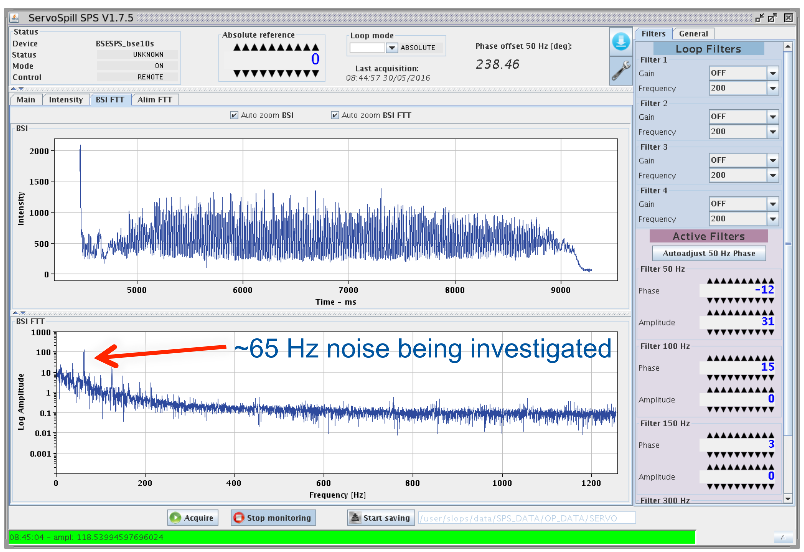
- *Autospill* is less sensitive to shot-to-shot intensity fluctuations
- Needs regular re-tuning as sensitive to super-cycle changes.
- Development is on-going to permit independent optimisation of first and second FT cycles



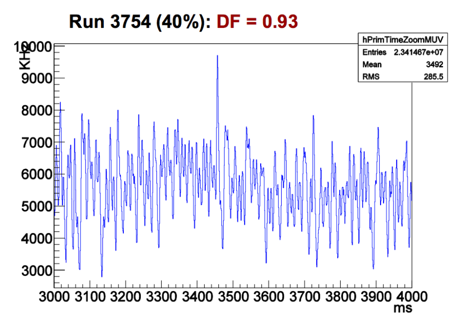
A well-tuned extraction in a stable super-cycle

Spill stability (2)

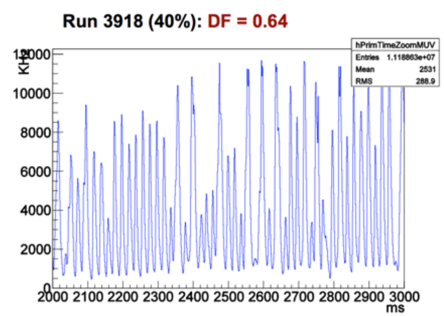
- 50 Hz mains harmonics are corrected in feed-forward with the servo quadrupoles in “anti-phase” (no longer feed-back mode):
  - Extracted intensity measured by SEM foils (BSI) inserted in beam
- Sensitive to drifts over ~24h and needs regular retuning:
  - An automatic tuning application is under development:



ServoSpill application on Monday



Well tuned
(duty factor = 93%)



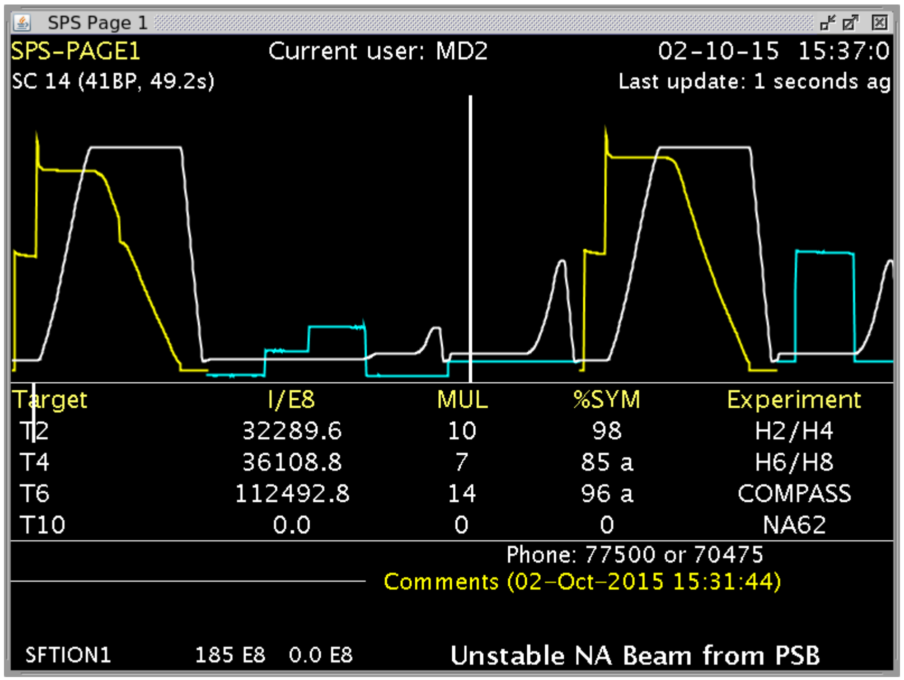
Not so well tuned
(duty factor = 64%)

Effective spill length is monitored online by the experiments, soon to be easily shared with OP: DF above computed with binning at ~1 ms and neglect microstructure, 10% lower with coincidence method

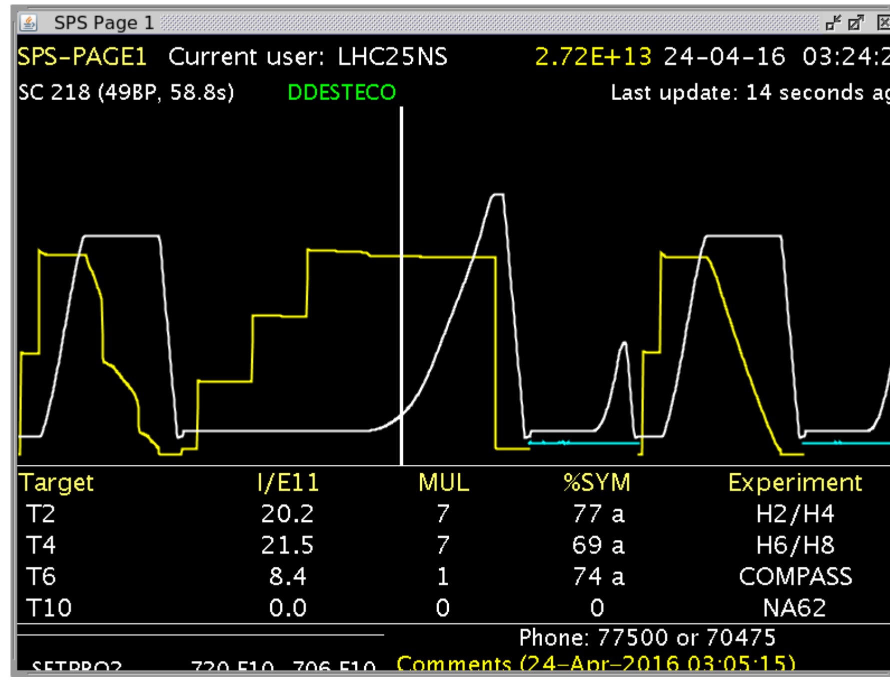
[5] Data provided by P. Petrov of UCL and NA62

QF power supply glitches

- Small current glitches (ΔI ~ 1 in 2000 A) observed recently during slow extraction: sporadic and, to date, without explanation.
- Glitches of ΔI/I ~ 10^{-3} (c.f. ~10^{-6} nom.) disrupt the slow-extraction.



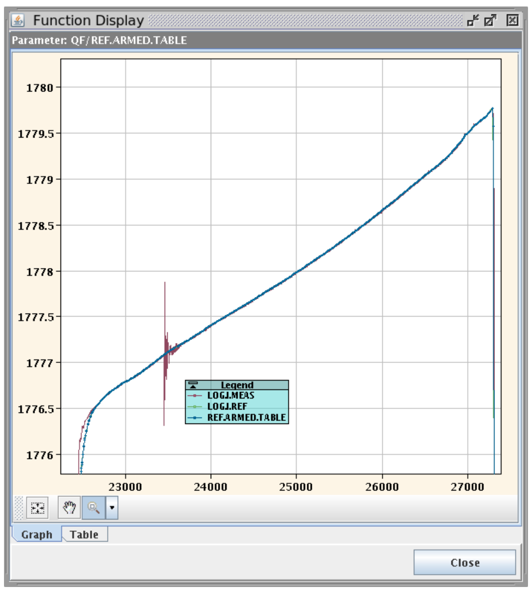
Glitch on 2nd October 2015

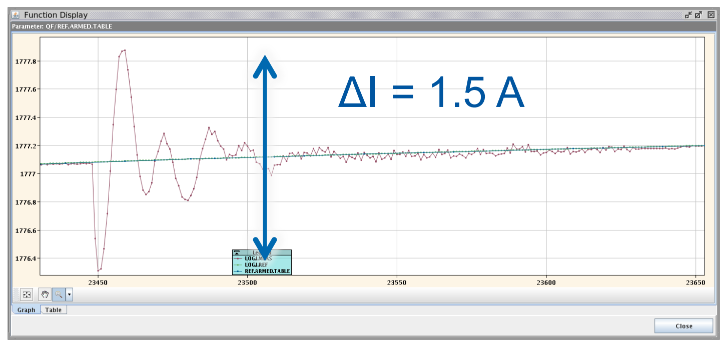


Glitch on 24th April 2016

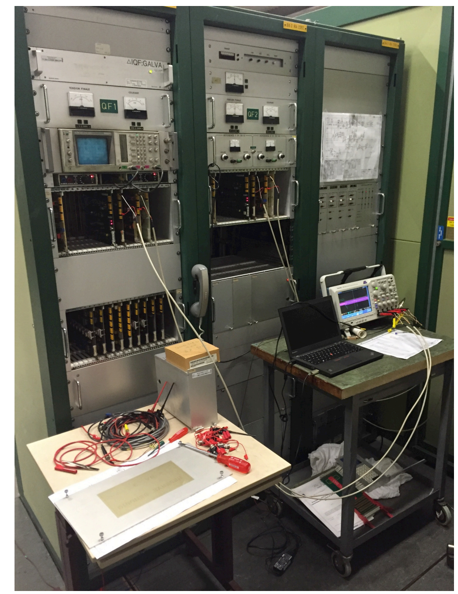
QF power supply glitches

- Small current glitches (ΔI ~ 1 in 2000 A) observed recently during slow extraction: sporadic and, to date, without explanation
- Glitches of ΔI/I ~ 10^{-3} (c.f. ~10^{-6} nom.) 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

Power supply stability

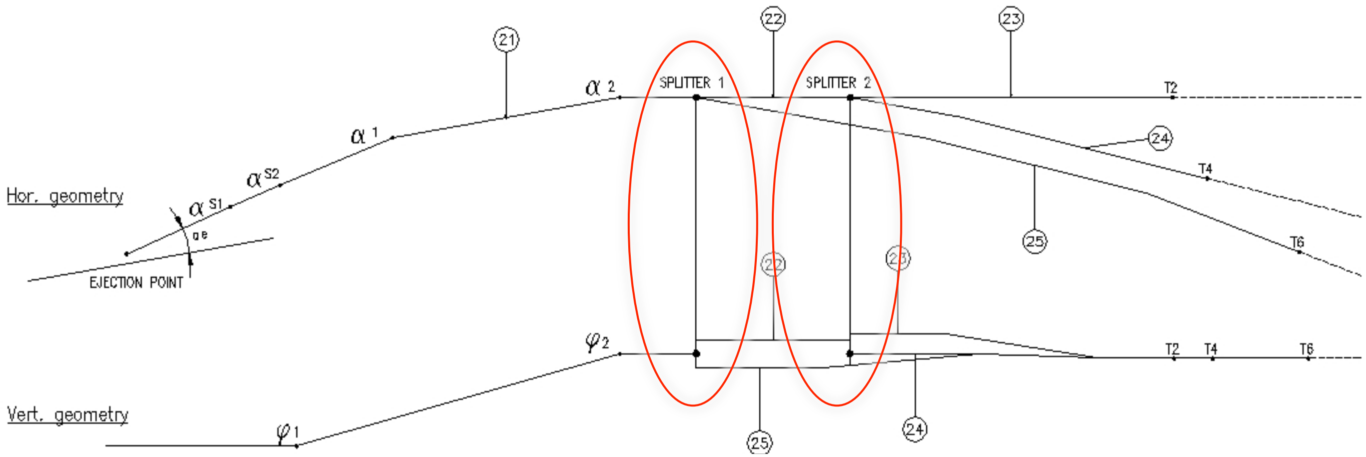
- General degradation of stability since the collider days is a known issue and seen on lifetime during coasting, e.g. UA9 physics.
- On-going consolidation of mains power supplies:
  - Transformers and thyristor bridges (rectifiers) replaced 2013
  - Still running with electronics designed by van der Meer (built to last!)
  - Digital current regulation presently being implemented
  - Electronics to be replaced in the future (not before LS2, >2019)
- Main complaint from experiments is the (n x 50) Hz noise when not properly compensated by the servo.
- Recent observations of other noise sources being investigated.

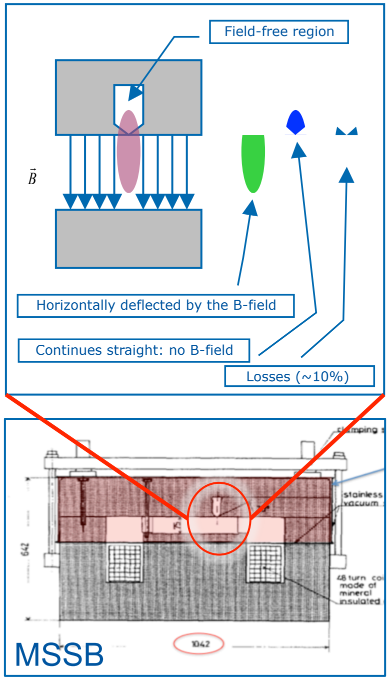
Mains power electronics control card

[6] K. Kahle, Q. King, G. Le Godec, Consolidation program SPS Main Power Converters, IEFC Workshop, 9 March 2012

Beam sharing in North Area

- Physical beam splitting used to share the spill to different experiments behind targets T2, T4 and T6:
  - NA61/SHINE, NA62, COMPASS etc.
  - Lose ~ 20% of beam intensity from SPS to targets
  - TCSC at MSSB up to ~50 mSv/hr (at contact, 2 months cooling)



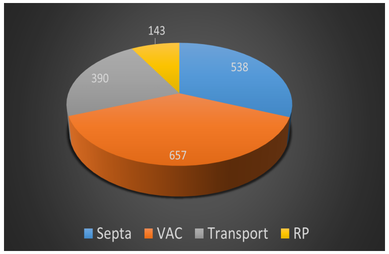


- Tuning of the beam line and transmission is limited by the available beam instrumentation (SEM foils) and their calibration (~10%).
- Splitting (probably) has to be avoided for future FT exp. proposals

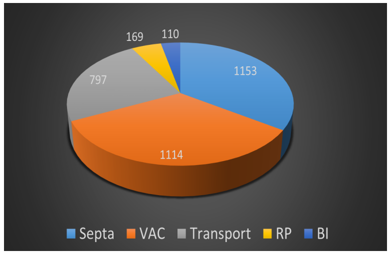
[7] L. Evans et al., The External Proton Beam Lines and the Splitter Systems of the CERN SPS, PAC'77, 16 – 18 March 1977

Maintenance of ZS

- Three ZS tank exchanges were required in 2015/16 shutdown:
  - ZS4 preventative replacement after sparking observed during 2015
  - ZS2 anode motorisation / clutch problem
  - Mechanical failure of replacement ZS2 tank (vertical aperture restriction)
- Interventions in high radiation area required (ALARA):
  - ~3 mSv/h at 40 cm after ~90 days during winter shutdown
  - Remote handling: employed for first time
  - Teamwork: transport, vacuum, radioprotection and septa groups
  - Steep learning curve: dose taken reduced by factor 2 with experience
  - Number of interventions: limited by dose to personnel (< 2 mSv/yr/person)



ZS4 exchange, 9 Feb 2016: 3.3 mSv (collective dose)



ZS2 exchange, 19 Feb 2016: 1.7 mSv (collective dose)


Remote handling in LSS2

[8] B. Balhan, YETS 2015-16 ZS replacement PM, EDMS 158381, 29 Feb 2016

Future challenges

- Understand and reduce machine activation (already in 2016)
- Control machine reproducibility and stability of FT cycle with increasingly flexible super-cycles
- Conventional wire-septum technology more-or-less at the limit, we will need an alternative:
- Revive crystal assisted extraction through dedicated MDs at SPS

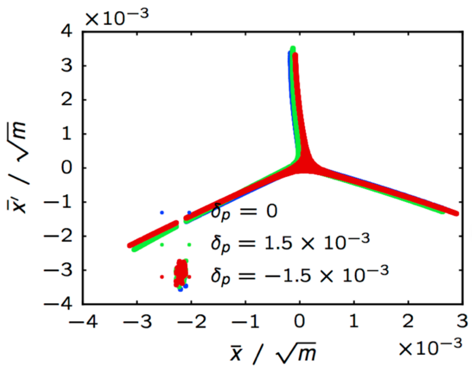
- Future proposed FT experiments at CERN requesting high intensity slow extracted p^+ beams at 400 GeV, e.g. SHiP

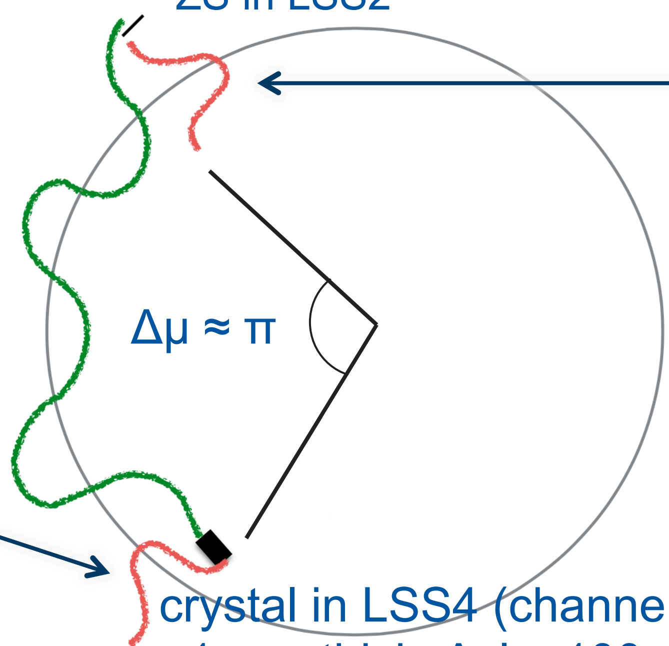
Crystal-assisted slow extraction

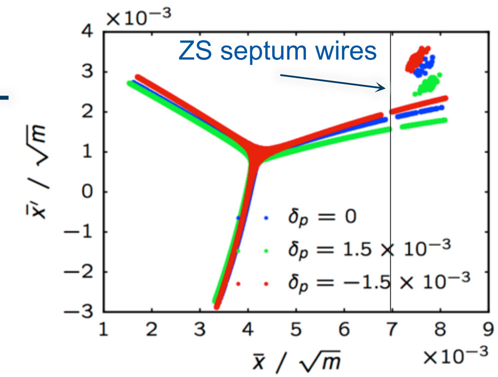
- Non-local non-resonant crystal assisted slow extraction to NA will be attempted this year in a dedicated MD session.
- Future ideas are being investigated:
  - e.g. non-local resonant crystal shadowing of ZS extraction, 2017 ?

ZS in LSS2

LSS4 crystal location
Identified (extraction bumpers)







crystal in LSS4 (channeling)
~1 mm thick, Δx' ~ 100 μrad

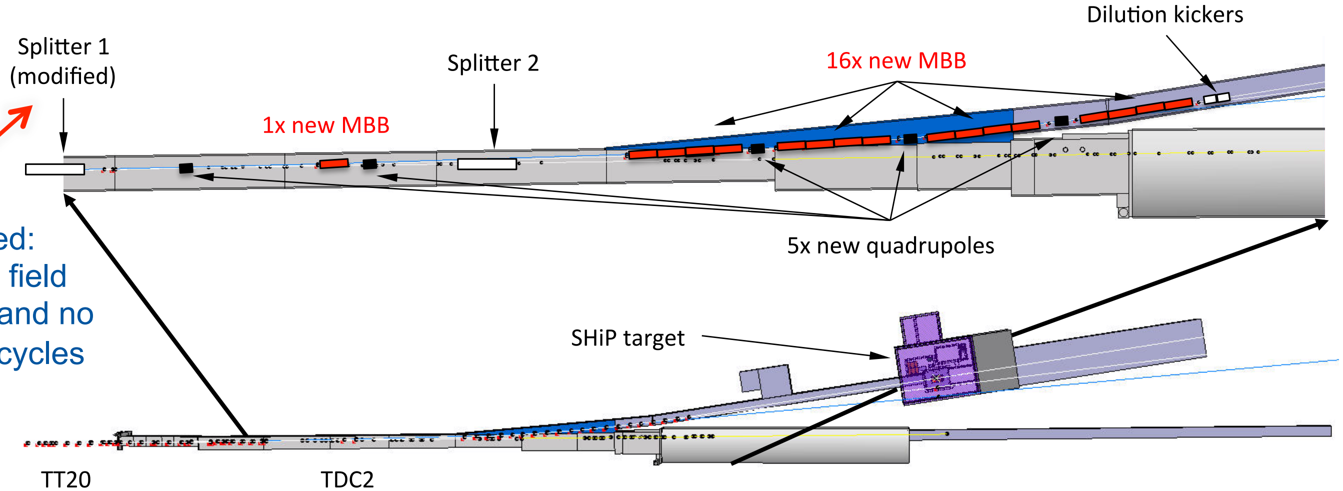
- Looking for factor of ~3 - 4 reduction in losses on ZS to bring future activation levels below today's.

[9] F. Velotti et al., Preliminary studies on non-local resonant crystal assisted slow extraction from SPS, UA0-SE Working Group, 29 March 2016

SHiP (Search for Hidden Particles)

- Technical Proposal published in April 2015
- Proposed experimental facility searching for Dark Matter:
  - Slow extracted spills of 4E13 p^+ over 1.2 s flat-top: intensities per spill has been delivered in the past but never so fast (challenging for spill quality!)
  - 3 MJ diluted over a target in 1 second
  - Total integrated p.o.t. of 200E18 over 5 years, i.e. x3 p.o.t. to WANF (1994-98), x1.1 p.o.t. to CNGS (fast ≈ lossless extraction)

To be laminated: pulsing opposite field (deflection to left) and no splitting for SHiP cycles



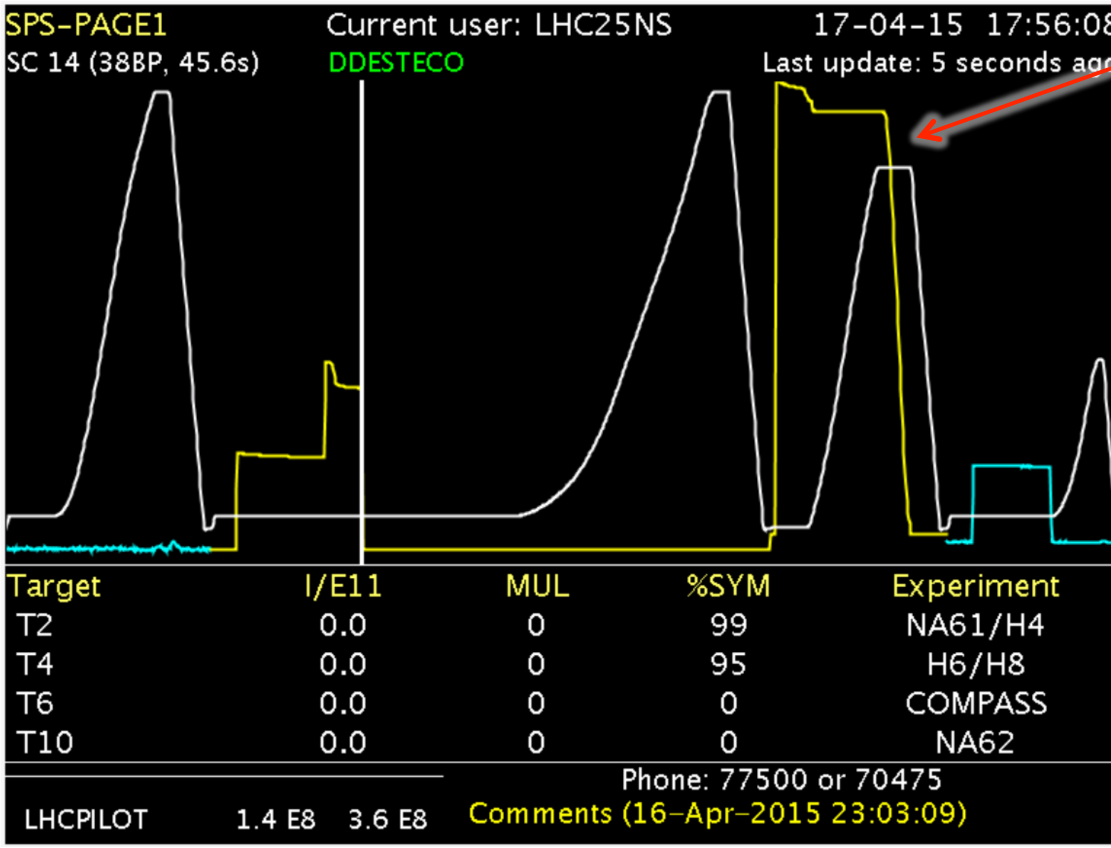
The proposed SHiP facility at SPS: LSS2

[10] A. Golutvin et al., A Facility to Search for Hidden Particles (SHiP) at the CERN SPS, CERN-SPSC-2015-016, 8 April 2015

SHiP (Search for Hidden Particles)

- First MDs and tests are underway:

This was not a beam dump!



SHiP MD in 2015: low intensity (~1E12 ppp) successfully extracted in 1.2 s

Summary

- We are regaining experience at CERN of operating at high intensities for high-energy Fixed Target physics with a multi-cycling SPS
- Increase of slow extraction losses (per p^+) is not fully understood
- Extraction losses have been reduced in 2016 but not yet to levels consistent with the recent past (e.g. CNGS 2008 - 2012)
- Indications that the machine stability and the changing super-cycle plays a role
- Investigations are on-going across different groups at CERN

- Interest in Fixed Target physics is not waning and requested intensities are increasing:

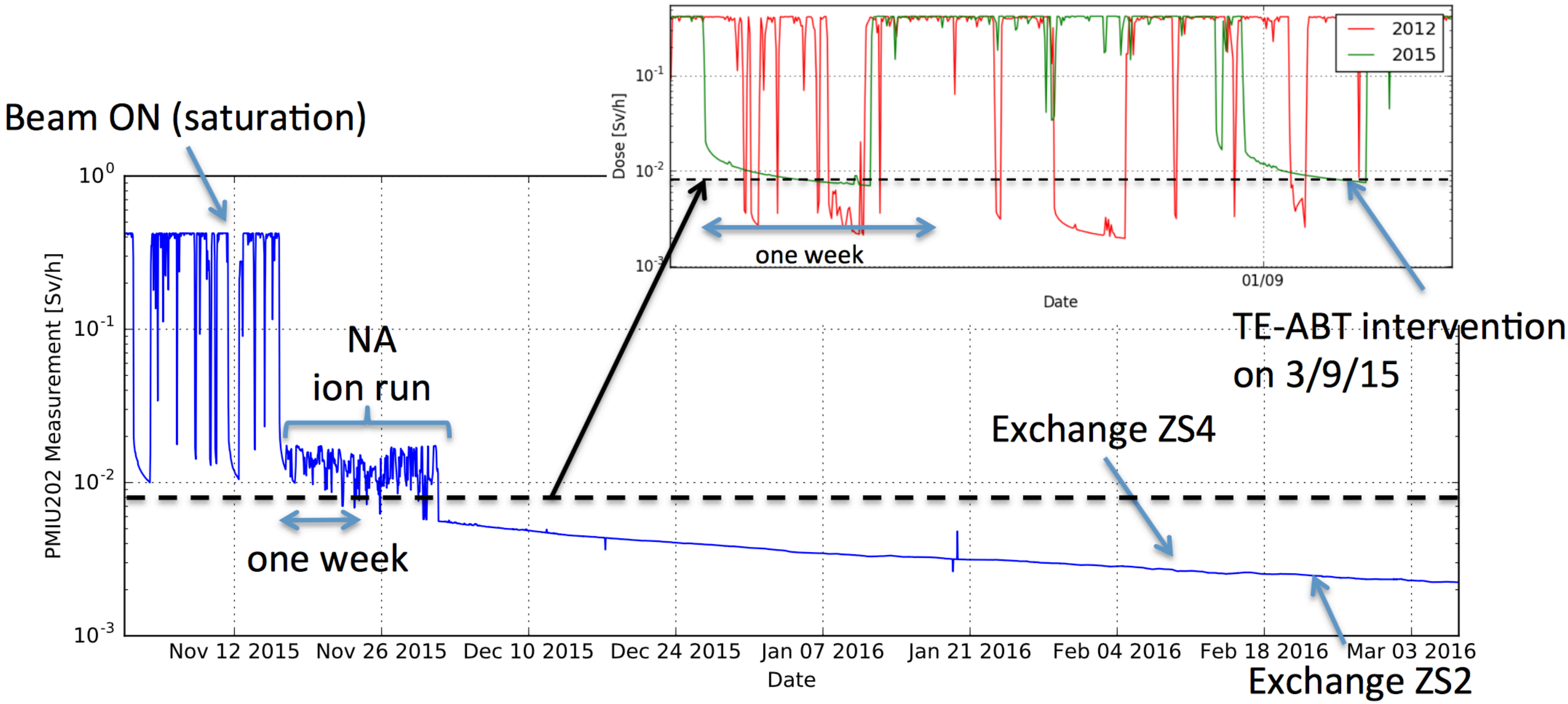
…focus has to be on extraction loss management!

Thank you for listening

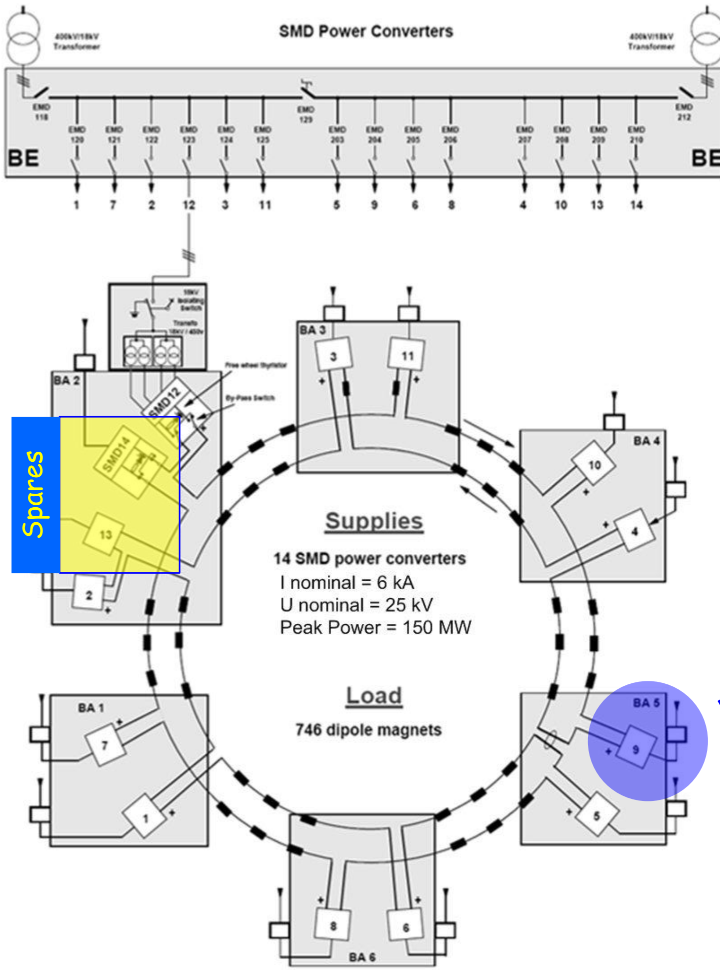
Extra slides

Cool-down during 2015-16 shutdown

- Cool-down as measured by PMIU202 under ZS Tank 3

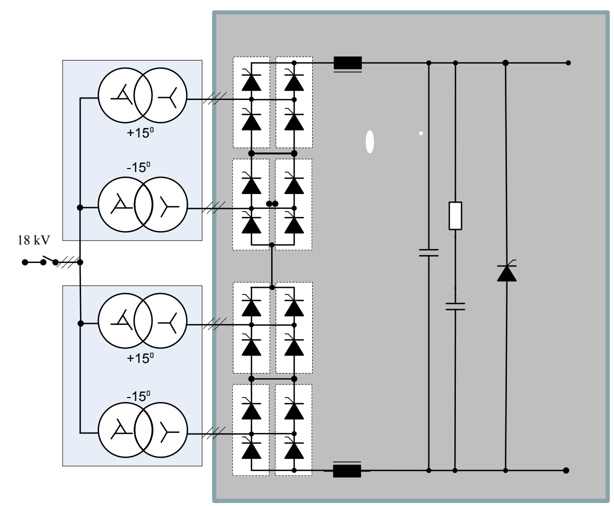


SMD converters



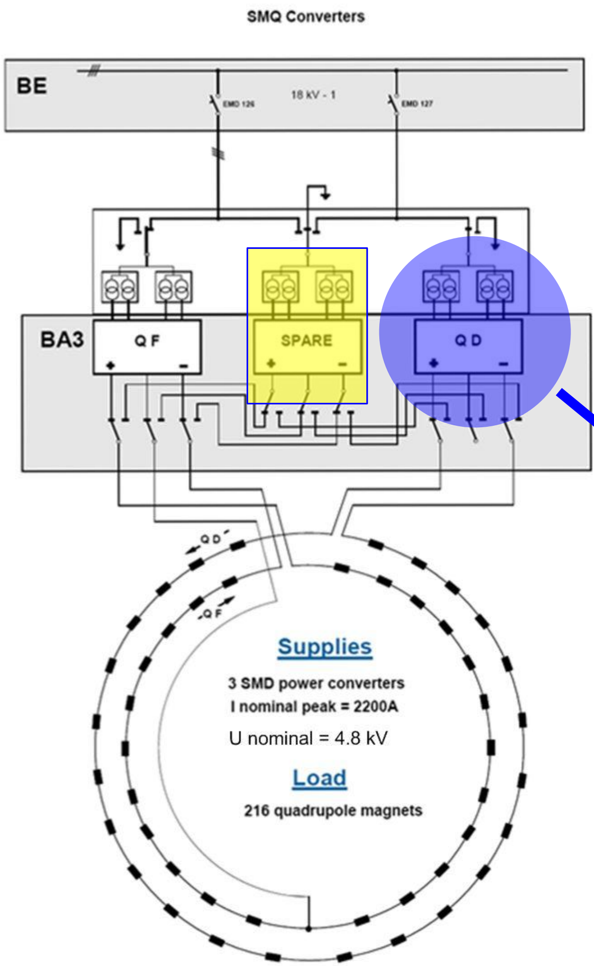
SPS Dipole Circuit

- Power system ratings: 25 kV/6kA/150 MW
- 12 converters connected in series
- 2 active spares.



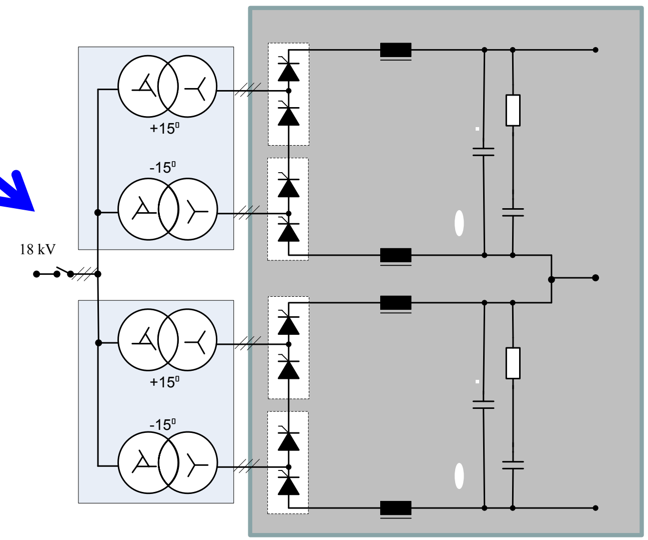
[6] K. Kahle, Q. King, G. Le Godec, Consolidation program SPS Main Power Converters, IEFC Workshop, 9 March 2012

SMQ converter



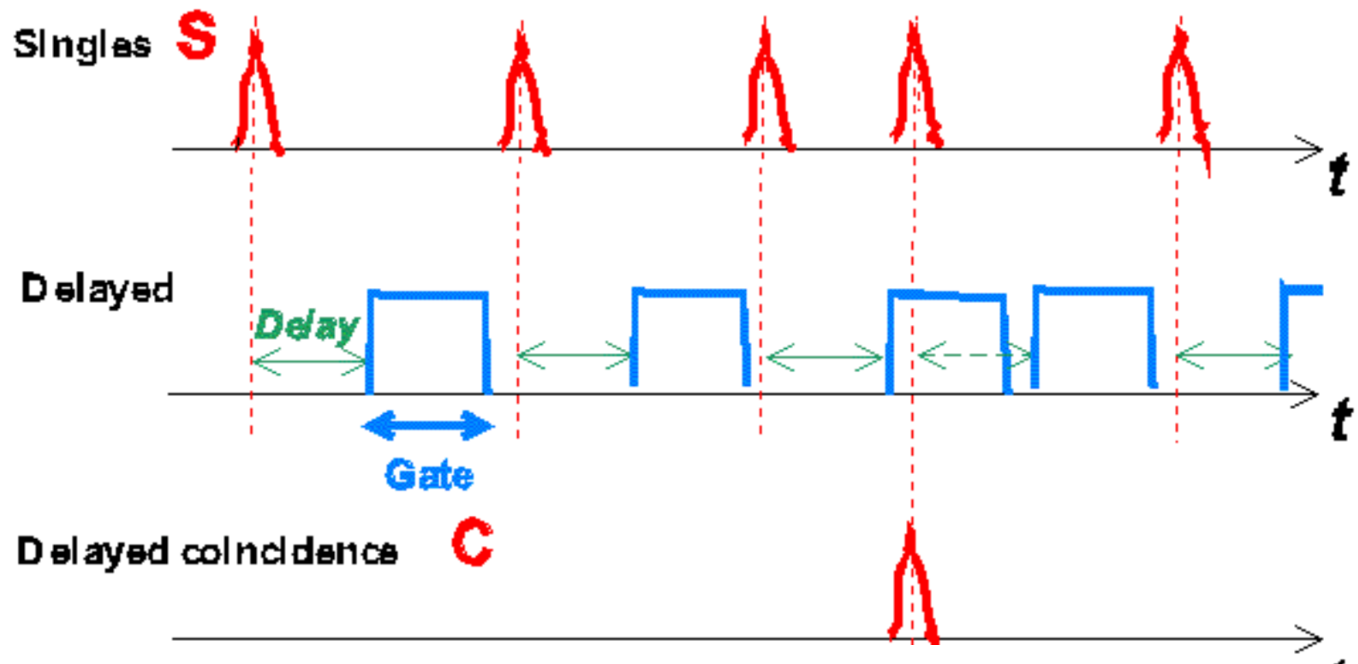
SPS Quadrupole Circuit

- Power system ratings: 4.8 kV/2.2 kA/ 10.6 MW
- 2 converters + 1 active spare



[6] K. Kahle, Q. King, G. Le Godec, Consolidation program SPS Main Power Converters, IEFC Workshop, 9 March 2012

Effective spill measurement



$$\text{Eff.Spill} = \text{Gate} \times \text{Singles}^2 / \text{Del.Coincidence}$$

- For every single signal a gate of with **Gate** is opened. The total time occupied by these gates is T_{open} = Singles x Gate.
- The number of coincidences in this time T_{open} is **C**, which is a fraction **F** = C/S of the total number of possible coincidences.
- The singles rate suffers also from deadtime with the same probability. Therefore T_{open} = Eff.Spill * **F**, which gives the formula quoted above.

[11] L. Gatignon

Dynamic economy mode

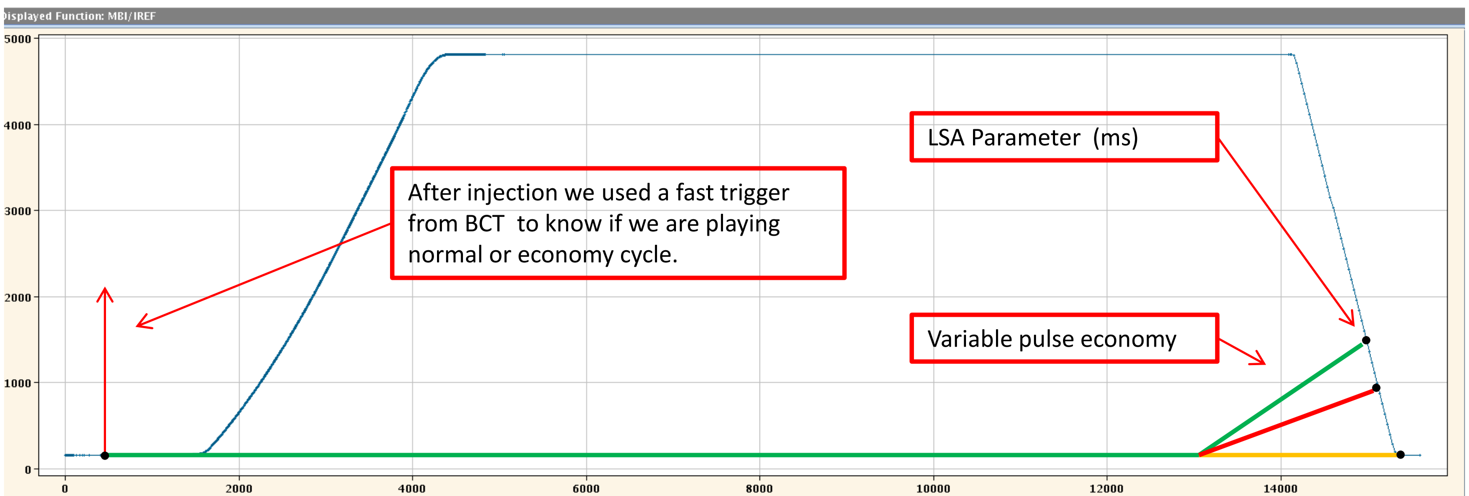
SPS Ring

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.

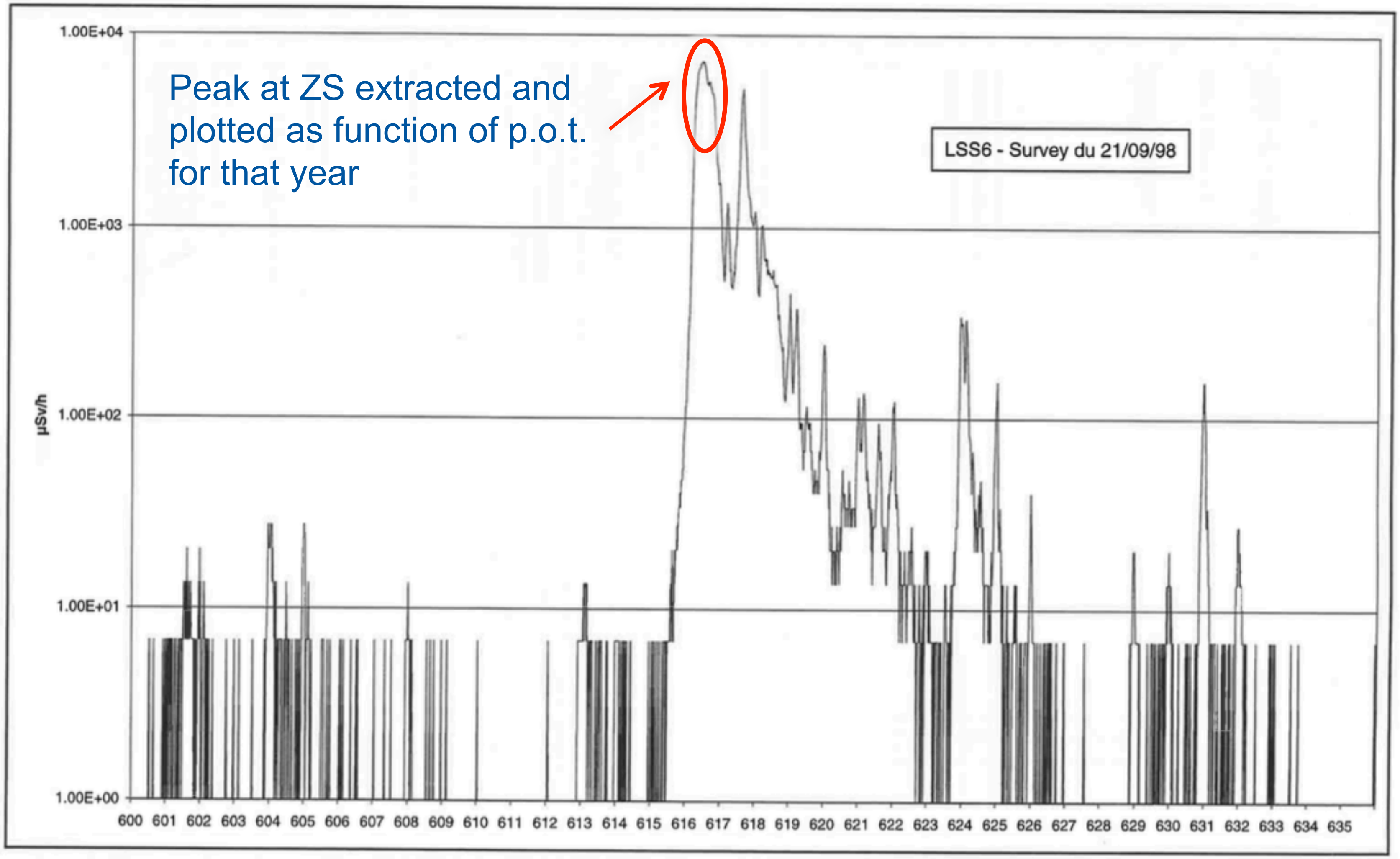
- MPS staying at injection energy.
- All ring circuits staying at Imin.
- All transfer line circuits without TT10 staying at Imin.

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.



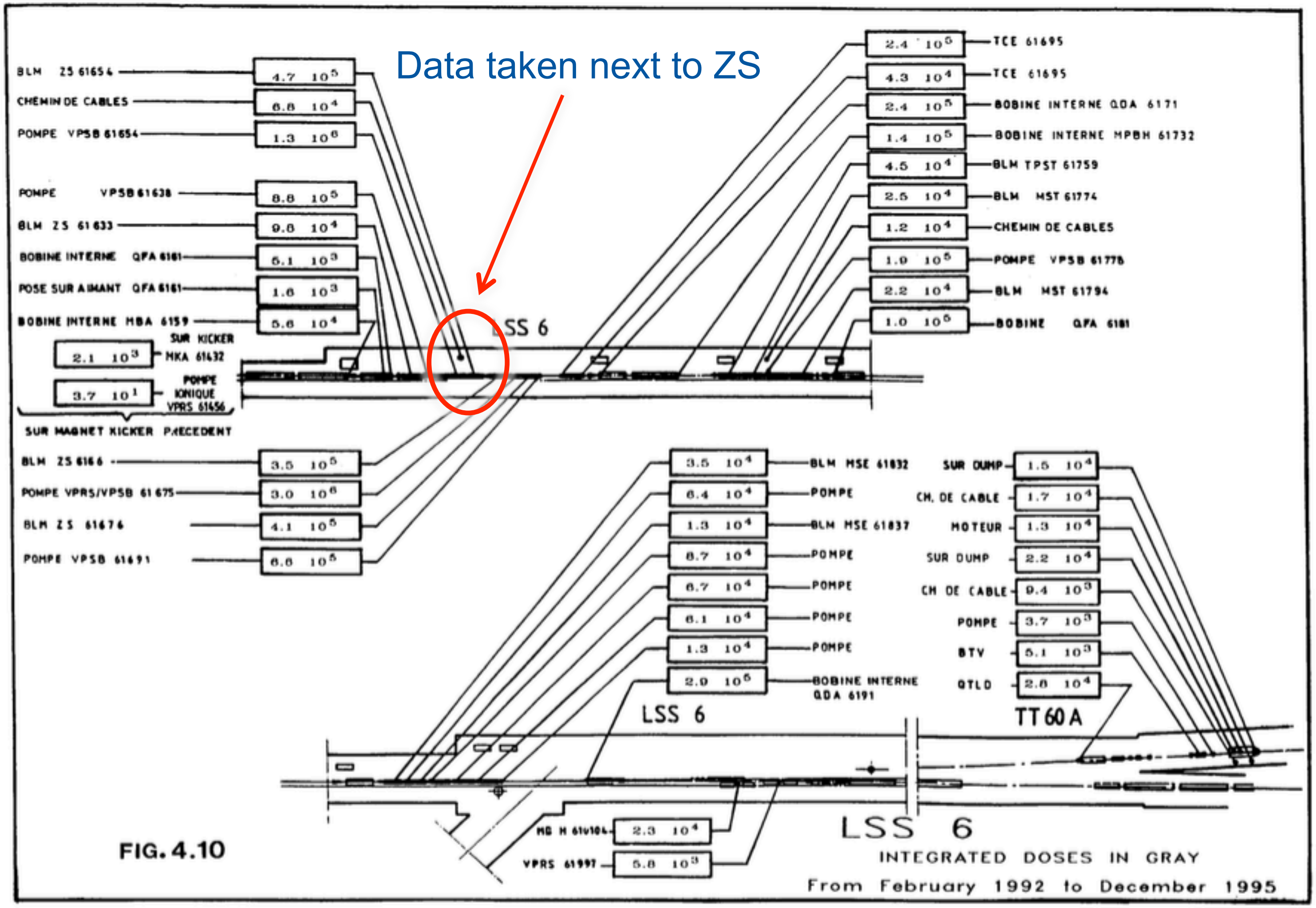
[11] S. Cettour Cave et al, SPS economy mode, MSWG meeting, CERN, 6 November 2015

RP survey LSS2, 1998 example:



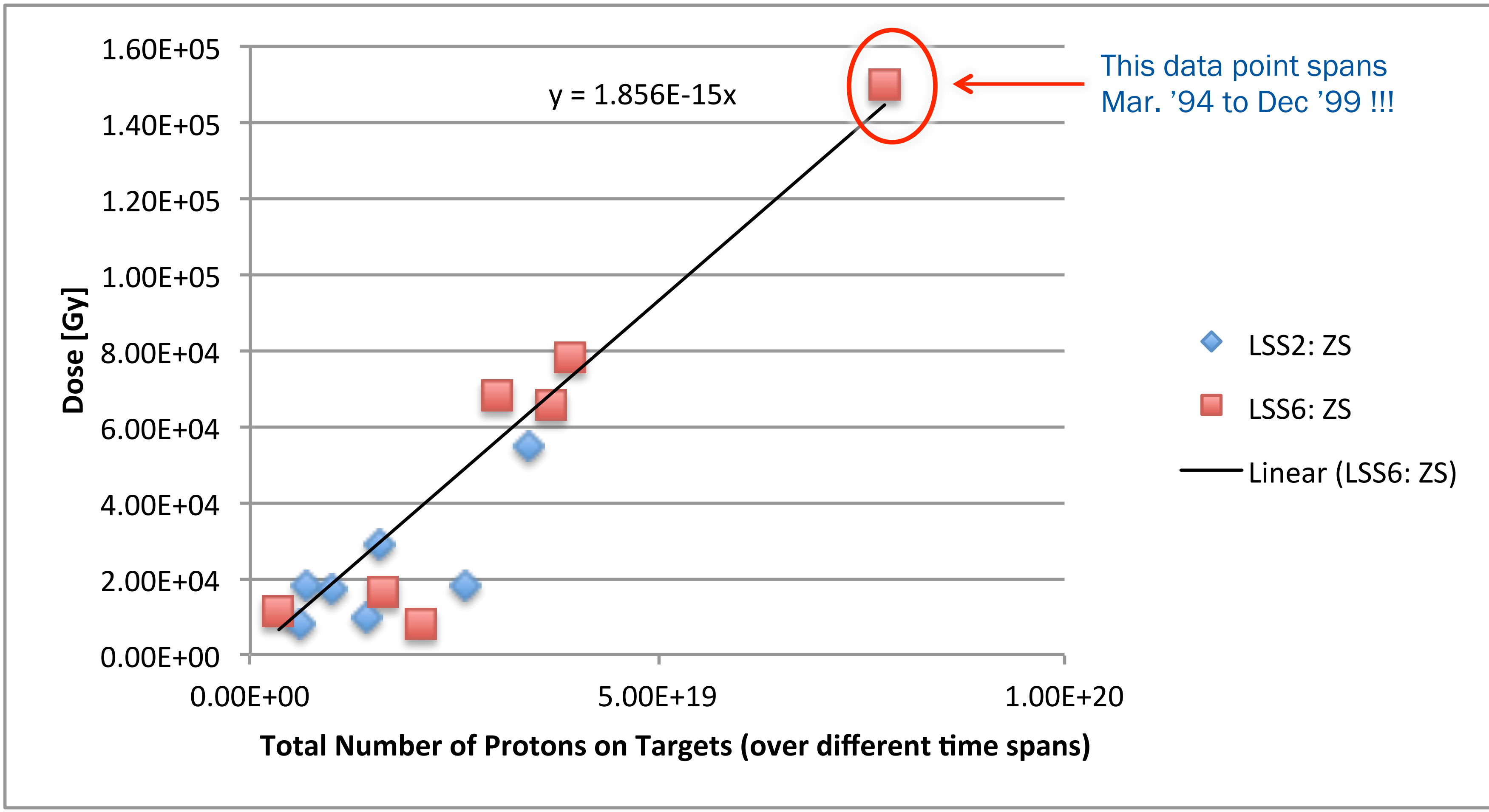
[12] SL Section Rapport Trimestriel: RSR-TRIM/S, CERN

High-level dosimetry



[12] SL Section Rapport Trimestriel: RSR-TRIM/S, CERN

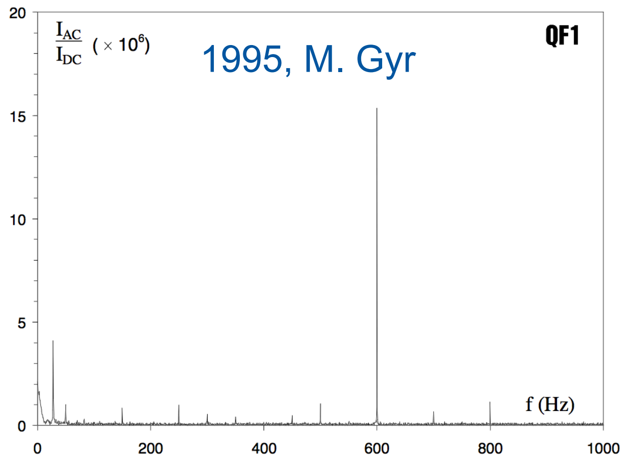
High-level dosimetry

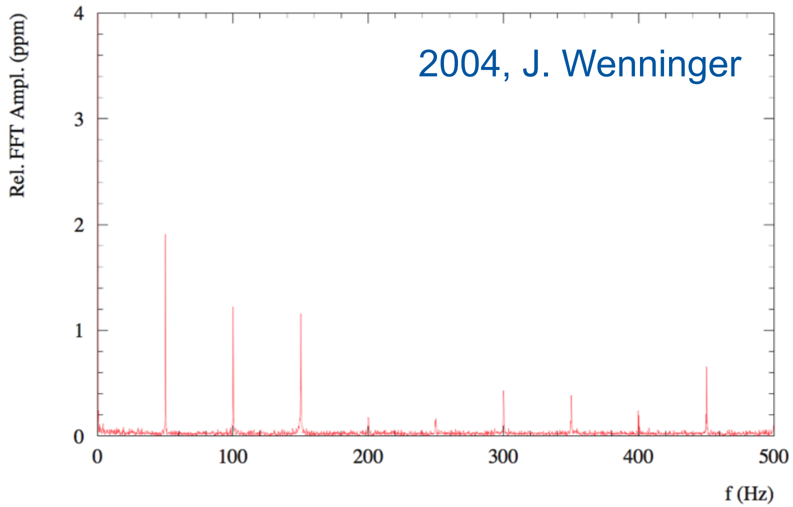


[12] SL Section Rapport Trimestriel: RSR-TRIM/S, CERN

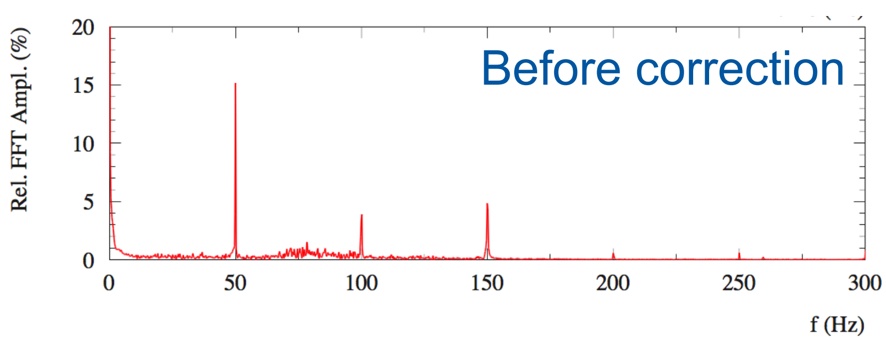
QF stability measurements

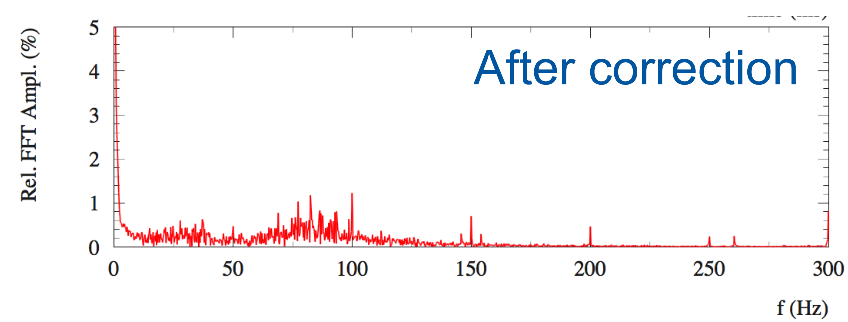
- Relative current ripples of ~10^{-6} measured



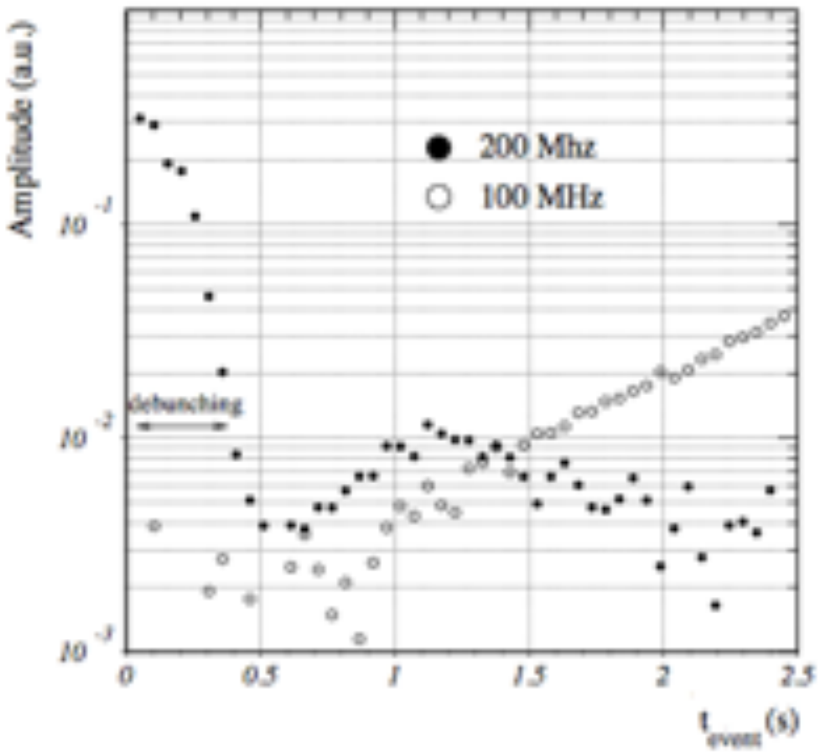


- Extracted beam structure





SPS spill structure



G.Collazuol, Measurement by NA48, Rate effects in the measurement of the direct CP violation with the NA48 experiment at CERN, Ph. D. thesis, Firenze, 2000.

NA duty cycle

- Duty-Cycle = FT length / SC length