Future Upgrade Scenarios for the Injector Complex

Upgrade possibilities in the SPS

E. Shaposhnikova for SPSU SG

LHC Performance Workshop – Chamonix,
28.01.2010
Outline

- Present status
- SPS limitations
- Possible actions
- Summary

Acknowledgments:
SPS Upgrade Study Group
BE/RF: T. Bohl, E. Ciapala, W. Hofle, T. Linnecar, E. Montesinos, J. Tuckmantel
SPS Upgrade Study Group

Study Group (BE, TE), since March 2007:

+ contributions from different groups (ABP, ABT, BI, MSC, OP, RF, VSC...)  
+ impedance team (chaired by E. Metral)

Main tasks:

• Identify limitations for intensity increase above nominal
• Study and propose solutions
• Design report with cost and planning for proposed actions

Meetings (~1/month), talks, minutes: [http://cern.ch/spsu/](http://cern.ch/spsu/)
# SPS: present achievements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SPS record at 450 GeV/c</th>
<th>LHC request 25 ns</th>
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<tbody>
<tr>
<td></td>
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<td>norm. H/V emitt. [µm]</td>
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<td>8/5</td>
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→ SPS upgrade is necessary for intensity above nominal LHC
# SPS beams with PS2

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<th>With PS2 at 50 (25) GeV/c</th>
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<td>50 ns LHC</td>
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<td>25 ns FT</td>
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<td></td>
<td>5.5 LHC</td>
<td>1.2 FT</td>
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<tr>
<td></td>
<td>1.2 FT</td>
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<tr>
<td>number of bunches</td>
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<td>total intensity /10^{13}</td>
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<td>4.6 815</td>
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<td>0.6 3.0</td>
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<td>norm. H/V emitt. [µm]</td>
<td>3.0 3.0</td>
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<td>9/6 FT</td>
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M. Benedikt et al., PS2 WG

28/01/2010
SPS upgrade for

I. Ultimate LHC intensity - 26 GeV/c injection
   – 1.7x10^{11}/bunch, 25 ns spacing, 288 bunches

II. PS2 max. intensity - 50 GeV/c injection
   – 4x10^{11}/bunch, 25 ns spacing, 336 bunches, total 1.3x10^{14}
   – 5.5x10^{11}/bunch, 50 ns spacing, 168 bunches
Intensity limitations identified

• **Single bunch effects:**
  – TMCI (transverse mode coupling instability)
  – space charge

• **Multi-bunch effects:**
  – beam loss
  – e-cloud
  – longitudinal coupled bunch instabilities
  – beam loading in the 200 MHz and 800 MHz RF systems
  – heating of machine elements (MKE, MKDV kickers, …)
  – vacuum (beam dump and MKDV outgassing), septum sparking
  (ZS was a main limitation in 2008 and 2009 → 3 nominal LHC batches)
Single bunch effects

Space charge
- Limit for space charge tune spread (ppbar): 0.07
- 26 GeV/c
  - nominal intensity: 0.05
  - ultimate intensity: 0.07
- 50 GeV/c
  - 5.5x10^{11} (max PS2): 0.06

Microwave instability
- After impedance reduction (2001) is not observed even for small long. emittances

TMCI
- Threshold intensity scales (matched voltage) \( \sim \varepsilon_L \eta \)
- Threshold (impedance model fit to measurements) \( \sim 1.4 \times 10^{11} \)

Cures: higher chromaticity, \( \varepsilon_L \), impedance reduction... but 40-50% of transverse SPS impedance is still unknown \( \rightarrow \) ongoing work (impedance team)

- 50 GeV/c – factor 2.5 increase in the TMCI threshold \( \sim \eta \)
  \( \rightarrow 3.5 \times 10^{11} \)
SPS limitations: beam loss

- Significant particle loss for nominal LHC beam (flat bottom + capture): from 20% at the beginning of year to 10% at the end
- Relative losses increase with beam intensity, strong dependence on batch intensity, less on total (number of batches)
- Much smaller (~5%) relative losses for 75 ns and 50 ns bunch spacing for the same bunch intensity → not single bunch effect; loss decrease during scrubbing run; different lifetime in the head and tail of batch → e-cloud?

To have the same absolute losses relative losses should be reduced for higher intensities
→ the origin of beam loss
→ e-cloud mitigation
→ beam collimation (?)
SPS limitations: e-cloud

- Pressure rise, transverse emittance blow-up, beam losses, instabilities
- **Cures**: scrubbing run, high V chromaticity, feedback (H)
- Beam energy dependence:
  - **H-plane**: e-cloud instability growth time ~ beam energy
  - **V-plane**: instability threshold is decreasing with energy
    (for constant norm. emittances, bunch length and matched voltage)

**Studies of the scaling law in the SPSU SG:**
- HEADTAIL simulations
- measurements during ramp with reduced chromaticity and damper gain
- special cycle with flat portion at 55 GeV/c \(\rightarrow\) dependence on transverse size confirmed (G. Rumolo et al. PRL, 100, 2008)
e-cloud mitigation

SPS requirements:

- applicable to the existing stainless steel vacuum chamber inside 6 m long magnets without dismantling
- no aperture reduction (thickness < 0.5 mm)
- no bake-out above 120 deg
- no re-activation
- no ageing with venting
- low impedance
- long-term stability
- good vacuum properties, no (small) outgassing
Possible e-cloud mitigation

• Coatings
  - low SEY amorphous carbon (a-C), SEY < 1 (1.3 is critical for SPS), stainless steel (StSt) – 2.5 (1.5 after scrubbing)
    o rough surfaces

• Clearing electrodes all along the beam pipe
  o fixing (needs 600-800 deg)
  o impedance

• Grooves (M. Pivi et al.)
  o manufacture, test with beam, aperture, impedance

• Active damping system in V plane (W. Hofle et al., LARP)
  o feasibility (instability growth rate, frequency)
  o large bandwidth
  o incoherent effects
e-cloud experimental set-up in 2008-2010

- 4 strip-line monitors XSD:
  - (1)-(2) St-St for reference and pressure measurement (new)
  - (3) - old a-C coating
  - (4) – a-CZr (rough)

- Clearing (enamel) electrodes with button PUs (2008)
- C - magnet with exchangeable samples (St-St in 2008, a-C in 2009)

Plus e-cloud set-ups in PS and Linac3 (a-C, clearing electrodes)
Possible vacuum chamber modification

- **2009:**
  - 3 MBB spare magnets coated with a-C (60 mm top & bottom)
  - installed in the SPS (LSS5) with microwave and vacuum diagnostics
  - MDs with LHC beam

- **2010:**
  - 1 MBB is out of ring for inspection
  - design of new coating system
  - modified microwave and vacuum diagnostics for 2 coated magnets

coating bench in bld. 867
Results for a-C coating

Liners:
• 300 times smaller e-signal in a-C than in StSt
• conditioning (scrubbing) even for small SEY
• no ageing for a-C liners exposed to the beam (4 times less signal in old a-C)

Magnets:
• absence of e-cloud confirmed by microwave transmission measurements (last MD in 2009),
• but no significant reduction in pressure rise

TiN coating was successfully used in PEP-II, but doesn’t work so far in SNS ring

M. Taborelli et al.

Chamonix 2010
a-C coating: open questions

- Long term behavior – ageing with venting and scrubbing
- What should be coated (dipoles, quadrupoles, pumping port shields + )?
- Coating quality control
- Pressure (outgassing)
AEC’09: anti e-cloud coatings (that do not require activation) workshop
CERN  12-13.10.2009 (with ACCNET)

40 participants, 13 external talks

CERN talks:
1 SPS upgrade plan & coating requirements – E. Shaposhnikova
2 What should be coated – G. Rumolo
3 Characterization of amorphous carbon coatings – M. Taborelli
4 Results on amorphous carbon coatings in e-cloud monitors of SPS – C. Yin Vallgren
5 Results and plans of CESR-TA experiments on low SEY coatings – S. Calatroni
6 Diagnostic of coating results – microwave measurements – S. Federmann
7 Diagnostics of coating results – pressure measurements – M. Taborelli
8 Impedance of coating – D. Seebacher
9 Amorphous carbon coating of SPS dipoles – P. Pinto Costa
10 Possible logistics of coating of SPS – J. Bauche
11 Clearing electrodes: the PS experience – E. Mahner
Possible vacuum chamber modification

Implementation in the SPS

• 750 vacuum chambers inside dipoles can be treated in 3-4 shutdowns

• Experience due to installation of RF shields (1999-2001) and refurbishing of the cooling circuits of dipoles (2007-2009)

• Infrastructure partially exists (ECX5 cavern - ø20 m)

• Vacuum system (for coated chamber) - minimize air exposure during shutdowns and interventions
**SPS limitations: impedance (1/2)**

- **1999-2001:** SPS impedance reduction in preparation for nominal LHC beam

- **2003-2006:** impedance increase due to re-installation of 8 MKE (extraction kickers for LHC) – main contribution to longitudinal broad-band impedance budget (beam measurements and simulations)

- **2007-2010:** small reduction (MKE) - not measurable yet

Quadrupole oscillation frequency as a function of bunch intensity: \( \text{slope} \sim \text{Im } \mathcal{Z}_{\text{eff}} \)
SPS limitations: impedance (2/2)

• Search for unknown impedances:
  - transverse (broad-band): only 60% known \(\rightarrow\) TMCI
  - longitudinal (narrow-band - HOMs) \(\rightarrow\) coupled-bunch instability
    \(\rightarrow\) SPS impedance budget from all elements (impedance team)

• Known high impedance elements:
  - **MKE** (M. Barnes): serigraphy (optimised?) – 3 done, 5 more in 3 years. Transverse impedance issue. New design?
  - **MKDV, MKDH**: 30 years old, no transition pieces between magnet and tank \(\rightarrow\) heating, outgassing with 50 ns (MKDV1) and 75 ns (MKDV2) spaced beams. Spare MKDV1 with trans. pieces is now in the ring - OK
  - **800 MHz TW cavities**: active damping \(\rightarrow\) RF feedback and feedforward (2009-2010), installation of probes in each cell (37/cavity)
SPS limitations: coupled-bunch instability

Threshold $\sim 1/5$ nominal LHC bunch intensity $\rightarrow$ FB, FF, dampers, 800 MHz RF (in bunch-short. mode) + controlled emittance blow-up: $0.42 \rightarrow 0.65$ eVs $\rightarrow$ larger emittance needed for higher intensities – more RF!
200 MHz RF system in the SPS

- 4 Travelling Wave cavities:
  - 2 of 5 sections
  - 2 of 4 sections
  - 11 cells/section
  - 18 sections + 2 spares
- Total voltage: **8.0 MV**
- Power/cavity (E. Montesinos):
  - 700 kW for full ring (CNGS)
  - 1(1.4) MW for half ring (LHC) - possible in pulsed mode (not tested yet)
  - limited by power amplifier, couplers and feeder lines
200 MHz RF system in the SPS

- Power (1 MW) and voltage (7.5 MV) limitations are still OK for acceleration of the ultimate LHC beam.
- But if larger emittances ($\varepsilon \sim \sqrt{N}$) are required for beam stability in the SPS or in LHC beam transfer to the LHC, a 400 MHz RF system becomes critical:
  
  \[ \tau \sim (\varepsilon / V^{1/2})^{1/2} \rightarrow \text{for } \tau = \text{const} \]
  
  \[ V = V_1 \frac{N_{\text{ult}}}{N_{\text{nom}}} = 1.48 \ V_1 = 10.3 \ MV \]

- Two possible solutions are:
  - to install the 200 MHz RF system in the LHC (E. Ciapala talk)
  - to rearrange the SPS 200 MHz RF program:
    - flat top - 7.5 MV
    - acceleration – max 4.5 MV
200 MHz TW RF system: voltage/cavity

- 5-section cavities become less efficient at ultimate LHC current for power limit of 1.4 MW/cavity (T. Bohl, Chamonix 2000) and “useless” for 1 MW/cavity
- More voltage can be obtained by rearranging existing 4 cavities into 5 (3x4+2x3 = 18) or 6 (2x4+4x3) cavities
- Total power increase by 25% or 50% (5 or 6 cavities)
SPS RF system modification: impedance reduction

Total beam (peak) impedance of the 200 MHz TW RF system

\[ Z = \frac{R}{8} \sum L_n^2 = RL^2/8 \sum (n-1/11)^2 \]

\( R = 27.1 \text{ kOhm/m}^2, \)
\( n \) - number of sections per cavity
\( L_n = L (n-1/11), \ L = 11 \times 0.374 \text{ m}, \ RL^2/8 = 57.3 \text{ kOhm} \)

4 cav. 2x5 & 2x4:  \( Z = 4.5 \text{ MOhm} \) - now
5 cav. 2x3 & 3x4:  \( Z = 3.6 \text{ MOhm} \) - 20% less
6 cav. 4x3 & 2x4:  \( Z = 3.7 \text{ MOhm} \) - 18% less

→ We have two more cavities in the SPS and reduce impedance!
(To compare with installation of the 200 MHz in LHC)
Total 200 MHz voltage on SPS flat top

- Existing configuration will have problems at ultimate LHC current even at 1 MW

- The same voltage for ultimate current as for nominal could be obtained with 6 cavities and power of 1 MW
FT/CNGS acceleration cycle

Limitation for voltage required for acceleration for \( P_{\text{max}} = 0.7 \text{ MW} \)

- Presently both voltage and power are at the limit: 7.5 MV used after transition crossing (uncontrolled emittance blow-up)
- Significant improvement for CNGS and fast LHC cycle with 6 cavities

4200 bunches spaced by 5 ns

0.73 A - RF current for \( N = 4.8 \times 10^{13} \) (nominal CNGS)
200 MHz TW RF system upgrade - summary

- **How many:** significant gain in voltage even with 5 cavities, restored performance for LHC ultimate beam and improved for CNGS with 6 cavities

- **Where:** 1 or 2 cavities in LSS5 in addition to 4 shorter cavities in LSS3 (now) – civil engineering, cavity and beam control

- **When:** start project now to be ready for 2015 (Linac4)

- For maximum PS2 intensities (5.2 A) – more short cavities and power, 2 power plants (2 feeder lines) per cavity, ...
FT/CNGS beam in SPS with PS2

With PS

One PS cycle ← one PS cycle →

- SPS filling factor 0.91
- Two gaps of 1.05 µs each
- Transition crossing
- No bunch-to-bucket transfer

With PS2

One PS2 cycle (5-turn extract.) ← →

- No transition crossing
- Bunch-to-bucket transfer
- No flat bottom
- SPS/PS2 geometrical gap: 0.6 µs, min PS2 kicker gap: 0.3 µs → max SPS gap of 0.9 µs (1.05 µs now) for the same SPS filling factor as now (0.91)
- CNGS beam: MKE rise time and kick length (max 12 µs now) → for fast extraction of full ring 5x1.05+0.6 = 5.85 µs total gap! → 0.9 µs kicker rise time and 22 µs kick length (B. Goddard)

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Internal beam dump (LSS1)

Limitations

- **TIDGV**: energy range 105-450 GeV, TIDH for beams < 37 GeV → no dumping possible in range (37-105) GeV
- **TIDVG** (M. Genbrugge, Y. Kadi, A. Stadler):
  - outgassing during dumps, pressure rise → interlock (MKP)
  - limits for dumping current and future beams (Antico T < 450°)
  - absorbs only 155 GeV/p (at 450 GeV)
  → New design for higher intensities
- **MKDV** (M. Barnes, B. Goddard):
  - injection at 50 GeV → larger dynamic range of the switch
  - kicker rise time >1 µs → beam gaps with PS2 (FT beam)
  - impedance (heating, outgassing))
  → Development of fast semiconductor switch
Hardware modifications

For ultimate LHC intensity

- ZS (electrostatic septa) – show-stopper for nominal LHC beam in 2008-2009
- Impedance reduction – MKE, MKDV, MKDH + more (as identified)
- SPS magnet coating after successful tests (in 2013/2014 ?)
- Vacuum system (for coated chamber)
- 200 MHz RF system, beam control,
  - transverse damper low-level control

Plus for PS2

- More RF power, cavities, beam control
- Transverse damper
- Beam dump (TIDVG)
- Dump kickers (MKDV/H), injection kickers (MKP)
- Beam collimation
- Radioprotection
- Beam instrumentation

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Summary

- Main SPS limitations for ultimate intensity have been identified, measures to overcome them are under study (limited by resources)
- Machine development (MD) sessions with higher than nominal intensity needed to see other possible limitations (obtained by scaling so far)
- Recent work in the SPSU SG is mainly concentrated on e-cloud mitigation, a-C coating of vacuum chamber is the best candidate for implementation
- The SPS RF system upgrade is required for ultimate intensities, also reduces pressure for installation of the capture system in LHC
- e-cloud mitigation, impedance reduction and RF upgrade would help for nominal and ultimate LHC beam operation and can be implemented earlier
- In the upgrade plan with PS2, the SPS will have a higher injection energy which helps to overcome some high intensity limitations (single bunch, injection losses) and avoid transition crossing for CNGS/FT beam. Needs many studies and hardware modifications.
Spare slides
Nominal LHC cycle in the SPS

200 MHz voltage program

Beam stability (Rsh [MOhm]) through the cycle in single and double RF

- Voltage for acceleration of the nominal LHC beam is well below limit except on flat top
- Flat top – transfer to 400 MHz LHC RF
200 MHz RF system for higher intensities – where?

### in LHC
- 8 bare cavities exist plus tuners and HOM damping loops from the SW 200 MHz; we have a low power coupler
- two identical systems (4 cavities/beam) → cost, maintenance
- reduce reliability
- no access during operation
- partial solution: beam still needs to be transferred to the 400 MHz RF system
- increase LHC impedance
- significantly (factor 4) reduce beam stability unless used with the 400 MHz RF system as a Landau cavity

### in SPS
- rearrange existing 4 cavities into 5 or 6 cavities of shorter length with 1 or 2 extra power plants to
  - reduce beam loading per cavity
  - increase available voltage (~number of cavities)
  - reduce beam coupling impedance
  - accessible on the surface
- necessary first step for further intensity increase in the SPS (with PS2 as injector)
SPSU budget in 2008-2012

<table>
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<th>Year</th>
<th>2008</th>
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</table>

Plus 10 man-years were foreseen

**2008:**
- SPS set-up for e-cloud tests
- samples, SEY measurements +UHV
- coating system design
- C-magnets, cables
- clearing electrodes, grooves
- PhD student (1/2 year)

**2009:**
- SPS set-up for e-cloud tests
- samples, SEY measurements
- coating system
- 3 SPS magnet coating & installation
- microwave diagnostics, cables

**2010:**
- coating system development: 234 kCHF
- residual gas analyser, calorimeter: 31 kCHF
- ...

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