Intensity Upgrade Plans for CERN/LHC Injector Complex

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for PAF and SPSU Working Groups

- **Motivation for upgrade**
- **New machines**
- **SPS upgrade**

Motivation for CERN injector upgrade

- **Future LHC upgrade:**
  - radiation damage of LHC IR Quads (~2016)
  - statistical error reduction saturates after a few years of nominal operation
  - physics motivation for **10 times** higher $\mathcal{L}$
    - 25% more discovery range in particle mass
    - 2 times higher precision

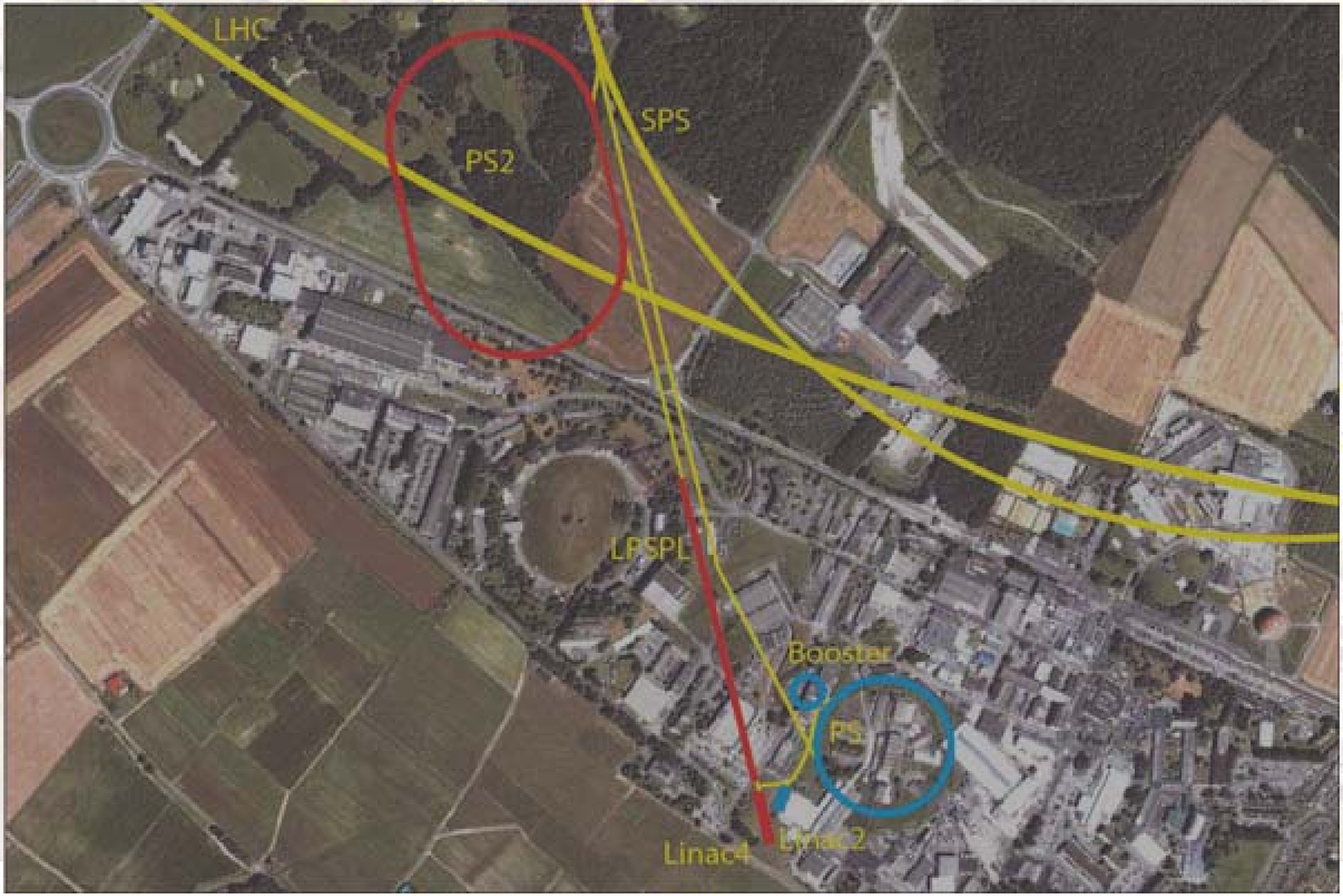
    ►**new beam requirements**
- **Age of the present injectors and need for reliable operation for the next X(?) years**
  - Linac2 1978
  - PSB 1975
  - PS 1959
  - SPS 1976
- **New experiments at low beam energy**

Present LHC upgrade scenarios

F. Zimmermann et al.

Parameter		Nominal	Ultimate	ES & FCC	LPA
bunch intensity	10^{11}	**1.15**	**1.7**	**1.7**	**4.9**
transv. emitt.	µm	3.75	3.75	3.75	3.75
bunch spacing	ns	25	25	**25**	**50**
beta* at IP1&5	m	0.55	0.5	0.08	0.25
crossing angle	µrad	285	315	0 & 673	381
peak lumi $\mathcal{L}$ average $\mathcal{L}$ (turnaround time 10h)	10^{34} $cm^{-2}s^{-1}$	1.0 0.46	2.3 0.91	**15.5** **2.4**	**10.7** **2.5**
event pile-up		19	44	294	403

LHC injectors: present and future



UNOSAT

Today's performance of the LHC injector chain (nominal parameters)

	Linac2	**PSB** (4 rings)	**PS**	**SPS**
energy	50 MeV	1.4 GeV	25 GeV	450 GeV
max bunch intensity		**1.5×10^{11}** (x12)	**1.3×10^{11}**	**1.15×10^{11}**
number of bunches		1 per ring	6 → 72	4 x 72
repetition x N pulses	1.2 s	2 x 1.2 s	4 x 3.6 s	12 x 21.6 s
intensity limitations	vacuum, RF triodes	space charge	space charge, radiation, CBI	e-cloud, CBI, TMCI, losses

CERN Council June 2007

Prospects for scientific activities over the period 2012-2016

Results available from LHC operation during the period 2008-2011 and from the activities proposed above should allow the CERN Council in 2010-2011 to decide on the future of CERN for more than one decade.

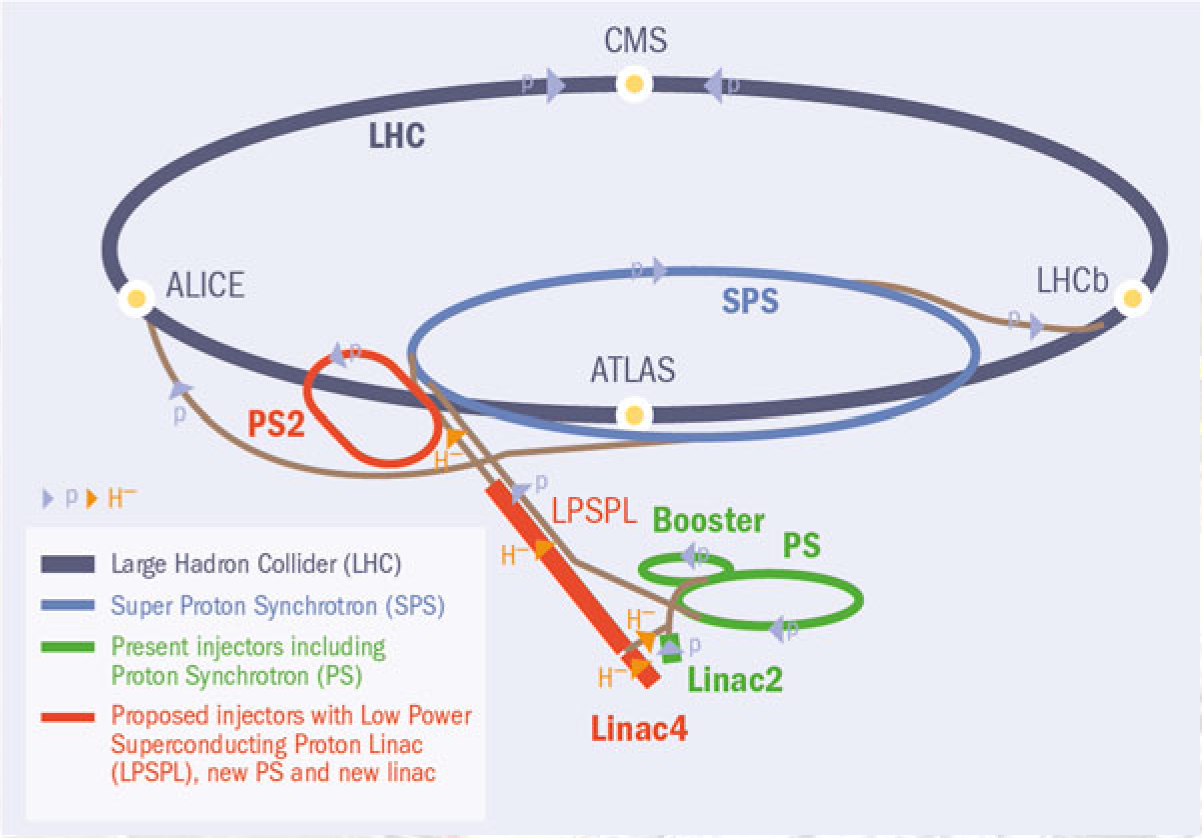
- If results from the LHC, as is highly likely, suggest the need for an increase in luminosity allowing a more extensive exploration of the new territory opened by the LHC, **a decision on the luminosity increase** (new RF system, new magnets for IR, increased cooling, new tracking in detectors, etc.) **will entail a simultaneous decision to build a new injector (SPL and PS) since higher LHC performance cannot be achieved reliably enough without a new injection line.**

R. Aymar, CERN DG, 2007

CERN future accelerators

New injectors

- Linac4 (2013)
  → 160 MeV
- LPSPL (2017)
  → 4 GeV
- PS2 (2017)
  → 50 GeV



Linac2 (50 MeV) → Linac4

H- — RFQ — chopper — DTL | CCDTL | PIMS →**160 GeV**

3 MeV (chopper) 50 MeV (DTL/CCDTL) 102 MeV (CCDTL/PIMS)

CERN Linac4 WG: http://linac4.web.cern.ch/linac4

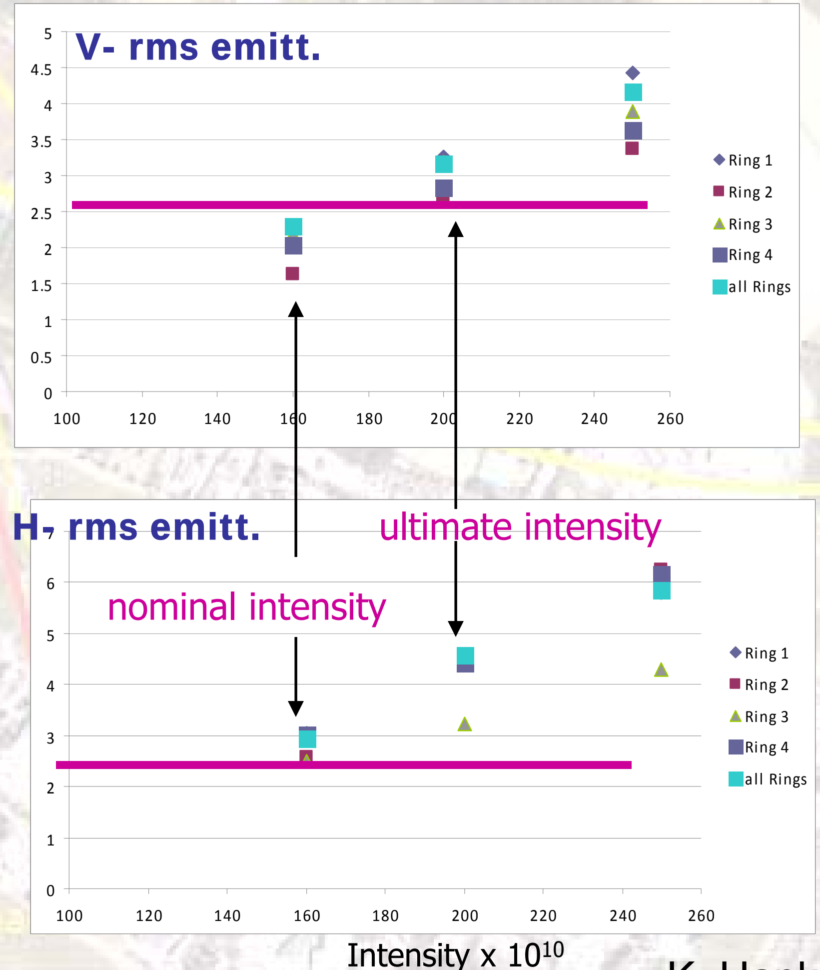
- PSB injection energy increase to 160 MeV
  → removal of the bottleneck due to space charge

  (more in talk of M. Martini in WG A)
- H^- injection → smaller transverse emittances
- Already approved project → construction phase
  (start of civil engineering – 16 October 2008)
- Beam parameters:
  - 10^{14} particles per beam pulse of 0.4 (1.2) ms
  - Repetition rate 1.1 (2) Hz
  - 5.1 kW beam power

  (more in talk of F. Gerigk in WG B)

PSB limitations: space charge

LHC beam, 2008



Transverse emittances (brightness):

- at the limit for nominal beam out of the SPS (due to losses in cascade of rings)
- out of reach for ultimate intensity
- operation with 3 RF systems/ring - emittance blow-up + bunch-lengthening mode

All 4 rings are the same but … different

K. Hanke

PSB (1.4 GeV) → (LP)SPL (4 GeV)

180 MeV | β=0.65 | β=0.65 | β=0.65 | 643 MeV | β=1.0 | β=1.0 | → **4 GeV**

- **Recent decisions:**
  - Choice between SPL and RCS
  - SPL (5 GeV, 4 MW) → LPSPL (4 GeV, 0.16 MW) with possible future upgrade
- **Beam parameters:**
  - 1.5 x10^{14} pp per pulse of 1.2 ms with 0.6 s repetition time
- **Ongoing studies:**
  - frequency choice: 700 MHz or 1400 MHz
  - cooling T choice: 2 or 4 deg K

→ Answers in talk of F. Gerigk in WG E

PS (25 GeV) → PS2 (50 GeV)

PS limitations:

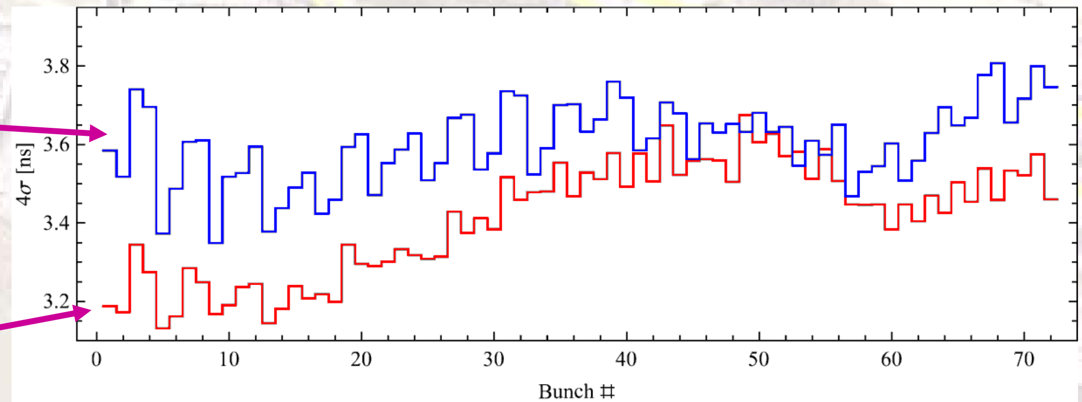
- space charge effects on the 1.2 s long flat bottom
  → injection energy increase with LPSPL to 4 GeV
- built on the surface → radiation problems → tunnel
- transition crossing (TMCI, ...)
- coupled bunch instabilities → controlled emittance blow-up, FB
- complicated RF gymnastics with 5 RF systems:
  (4+2) PSB bunches split → 72 bunches
- longitudinal matching with SPS (200 MHz RF)
- e-cloud for slightly shorter bunches
- ...

PS (25 GeV) → PS2 (50 GeV)
PS limitations: matching with SPS

Bunch length along LHC batch at extraction from PS

2x80 MHz cavities (normal operation)

3x80 MHz cavities (“shorter” bunches)



H. Damerau

PS2 design (4 GeV - 50 GeV)

CERN PS2 Working Group: http://paf-ps2.web.cern.ch/paf-ps2/

- Size: 1346 m = 15/77 of SPS – defined by energy range, 5-turn extraction for FT beam, and 25, 50 and 75 ns spaced LHC bunches
- Cycling time: 2.4 s to 50 GeV using normal conducting magnets (maximum ramp rate 1.5 T/s)
- "Brute force":
  - maximum effective beam power 400 kW (60 kW in present PS)
  - energy per beam pulse 1 MJ (70 kJ in present PS)
- Optics studies (- talk of Y. Papaphillippou in WG E):
  - real transition gamma γ_{tr} (transition jump)
  - imaginary γ_{tr} - no transition crossing
- Choice of main RF system/frequency:
  - 10 MHz + ... - copy of PS (PS2=PSx2)
  - 40 MHz (SPL chopping) - ~octave tuning range needed

SPS: present achievements and future needs

Parameters	PS2 offer per cycle at 50 GeV			SPS record at 450 GeV		LHC request at 450 GeV	
	25 ns	50 ns	FT	25 ns	FT	25 ns	50 ns
bunch intensity $/10^{11}$	4.4	**5.5**	1.6	**1.2**	0.13	1.7	**5.0**
number of bunches	168	84	840	288	4200	336	168
total intensity $/10^{13}$	7.4	4.6	**12.0**	3.5	**5.3**	5.7	8.4
long. emittance [eVs]	0.6	0.7	0.4	0.6	0.8	<1.0	<1.0
norm. H/V emitt. [μm]	3.5	3.5	15/8	3.5	8/5	3.5	3.5

→ **SPS upgrade is necessary**

SPS → SPSU(pgrade)

CERN SPSU Working Group: http://paf-spsu.web.cern.ch/paf-spsu/

Ultimate goals:

- Reliably provide the LHC with the beam required for reaching ten times the nominal luminosity
- Optimum use of possibilities offered by the new injectors both for the LHC and other users (FT, CNGS...)

Main tasks:

- Identify limitations in the existing SPS
- Study and propose solutions
- Design report in 2011 with cost and planning for proposed actions

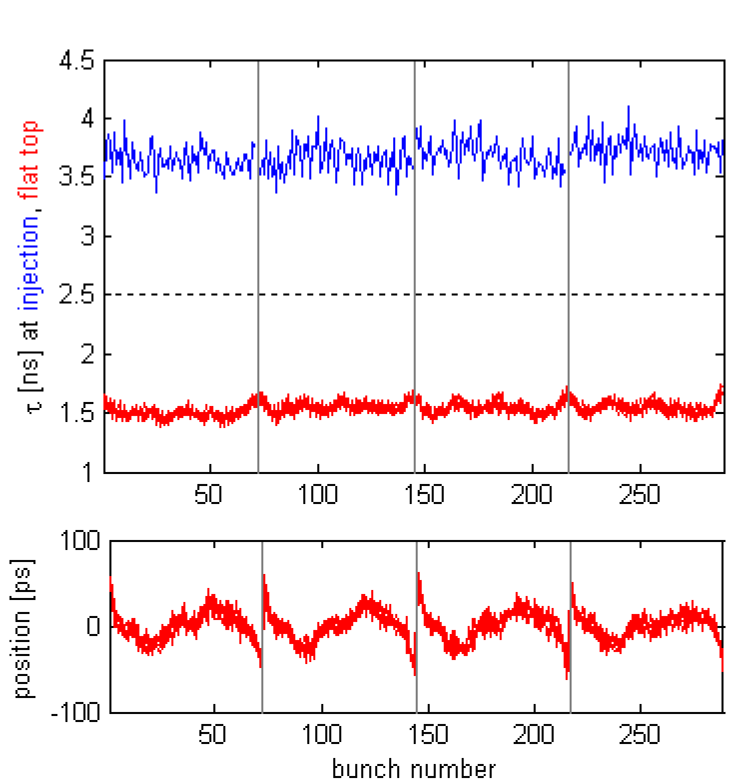
Initial studies in PAF WG (chairman - R. Garoby) → White Paper

SPSU Study Team exists since March 2007

SPS: today's status of nominal LHC beam

- bunch intensity: 1.15 10^{11}
- 4 batches of 72 bunches spaced at 25 ns
- bunch length: 1.6 ± 0.1 ns
- bunch position < 100 ps
- longitudinal emittance:
  0.6 ± 0.1 eVs
- transverse normalised emittances:
  - H-plane 3.0 ± 0.3 μm
  - V-plane: 3.6 ± 0.3 μm

Bunch length and position over 4 LHC batches at injection and flat top



G. Papotti et al., 2008

SPS: known intensity limitations

- **Single bunch effects:**
  - space charge (now only with ions)
  - TMCI (transverse mode coupling instability)
- **Multi-bunch effects:**
  - e-cloud
  - coupled bunch instabilities at injection and high energy
  - beam loss
  - beam loading in the 200 MHz and 800 MHz RF systems
  - heating of machine elements (MKE kickers)
  - vacuum – beam dump outgasing, septum sparking

SPSU: possible actions and cures

- Higher injection energy: 25 → 50 GeV with PS2
- Impedance reduction (after identification)
- Vacuum chamber modification for e-cloud mitigation
- Damping of instabilities:
  - active: upgrade of beam control (transverse and longitudinal feedbacks) – foreseen by White Paper
  - “passive”: due to increased nonlinearity
    - 800 MHz (4th harmonic) RF system
    - increased longitudinal emittance
- Hardware modifications: injection kickers, RF system, beam dump system, collimation, beam diagnostics, radioprotection

SPS: single bunch limitations with 50 GeV injection

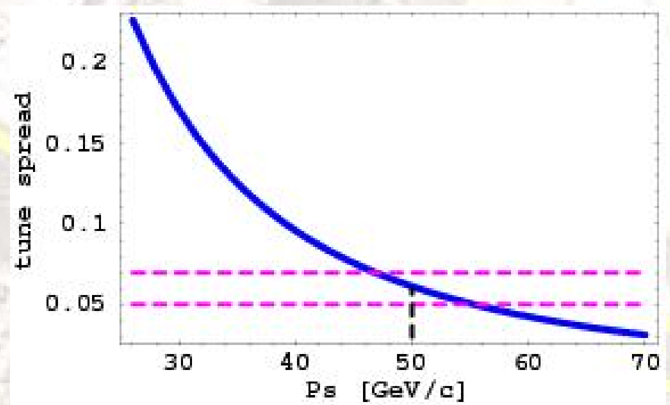
- Space charge tune spread at 26 GeV/c
  - nominal intensity: 0.05
  - ultimate : 0.07 (limit)
  - upgrade (5.5 $x10^{11}$): 0.23

  Sufficient improvement at 50 GeV for 5.5 $x10^{11}$? → More in talk of E. Metral

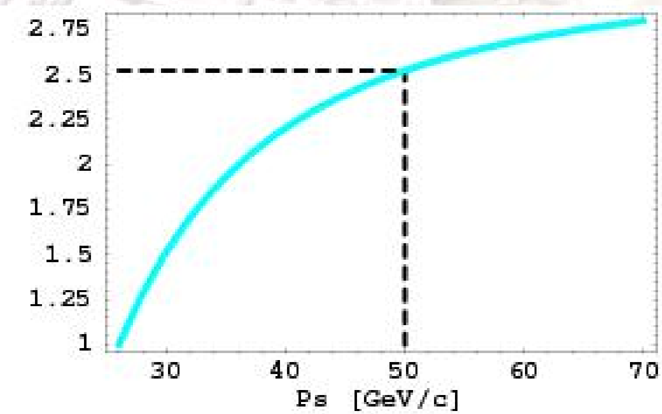
- The TMCI threshold ~ $\varepsilon_L \eta$
  - at 1.4 $x10^{11}$ now for 0.35 eVs
  - will be 2.5 higher at 50 GeV (η) (More in talk of B. Salvant)

→ Emittance increase to 0.6 eVs needed for 5.5 $x10^{11}$ at 50 GeV

Relative tune spread for upgrade intensity



Relative TMCI threshold

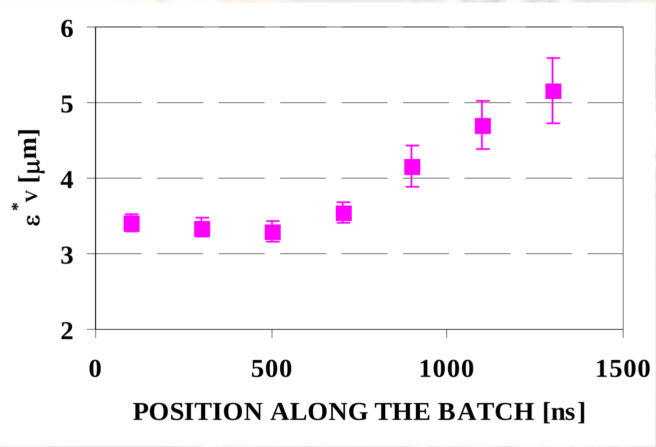


SPS with PS2 and 50 GeV injection

- Shorter injection plateau (2.4 s instead of 10.8 s) and acceleration time (10%) – shorter LHC filling time (and turnaround time)
- No transition crossing for all proton beams and probably light ions
- Easier acceleration of heavy ions (lead):
  - smaller tune spread and IBS growth rate,
  - smaller frequency sweep - no need for fixed frequency acceleration
- Smaller physical transverse emittance – less injection losses

SPS limitations: e-cloud

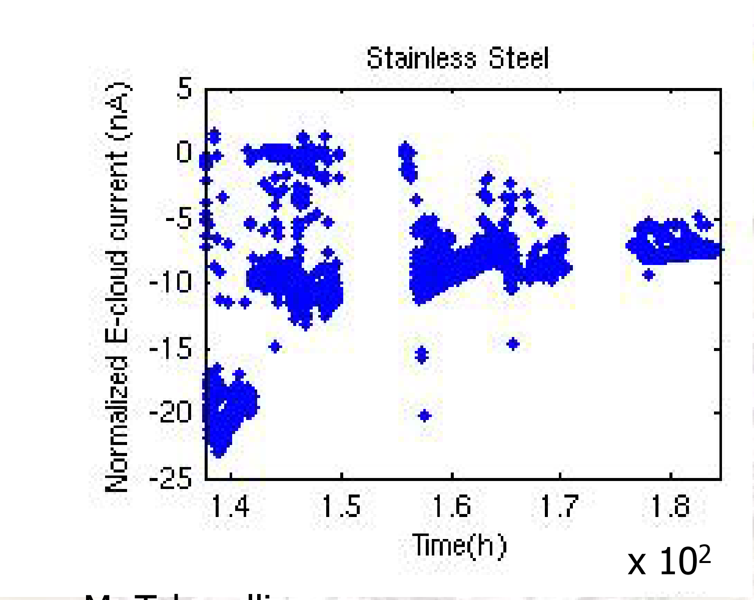
- pressure rise, septum sparking, beam dump enhanced outgasing
- beam losses
- transverse emittance blow-up and instabilities:
  - coupled bunch in H-plane
  - single bunch in V-plane



G. Arduini

Today's cures

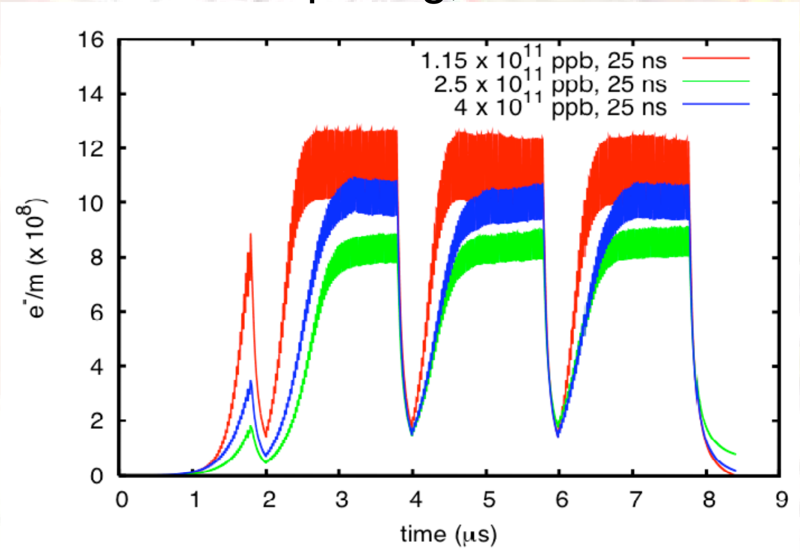
- high chromaticity in V-plane
- transverse damper in H-plane
- scrubbing run (from 2002): SEY decrease 2.5 → 1.5



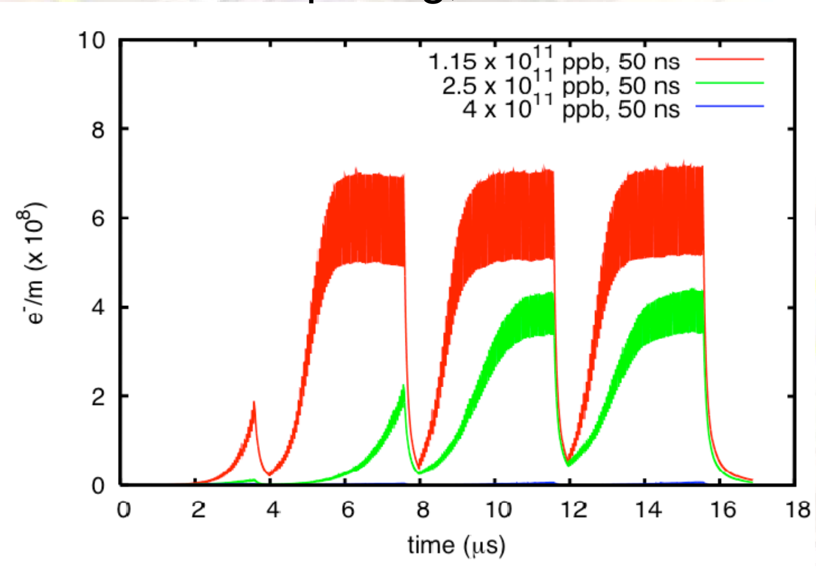
M. Taborelli

SPS limitations: e-cloud
Scaling with bunch spacing and intensity

25 ns spacing, SEY=1.4



50 ns spacing, SEY=1.6

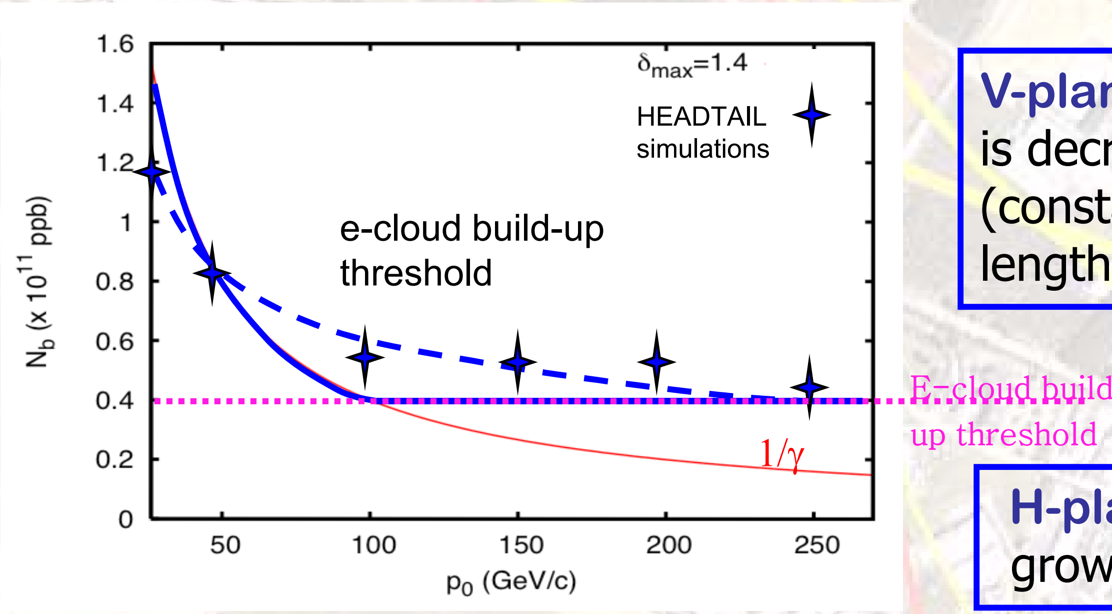


E-cloud build-up - results from HEADTAIL simulations (G. Rumolo et al.):

→ Non-monotonic dependence on bunch intensity for fixed spacing and SEY

→ For **50 ns spacing** a higher intensity is always better

SPS limitations: e-cloud
Scaling with beam energy



V-plane: instability threshold is decreasing with energy γ (constant emittances, bunch length and matched voltage)

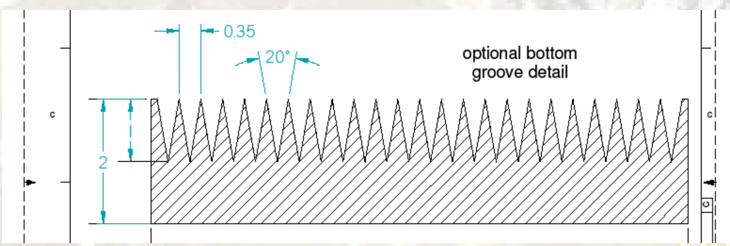
H-plane: e-cloud instability growth time ~γ

Experimental studies of the scaling law in the SPS:

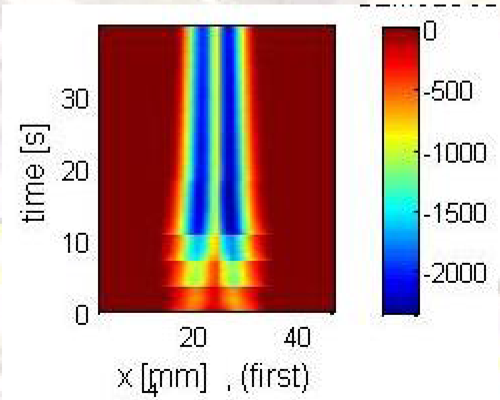
- 2006: measurements at different points during ramp with reduced chromaticity and damper gain – difficulties in interpretation
- 2007: special cycle with flat portion at 55 GeV/c, dependence on transverse size was confirmed (G. Rumolo et al. PRL, 100, 2008)

SPS upgrade: e-cloud mitigation

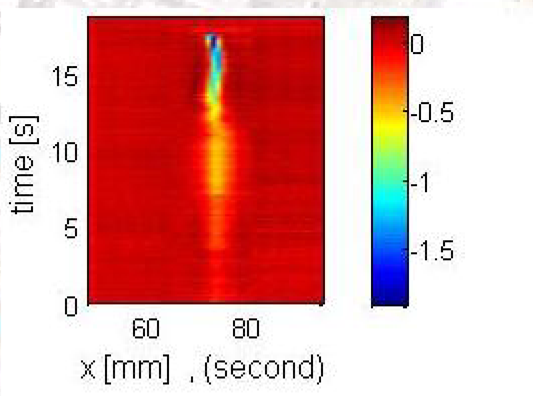
- requirements for surface coating: in-situ, no aperture reduction, no re-activation:
  - carbon based composites, SEY<1 obtained, - ageing problem (with venting)
  - rough metal surfaces (gold and cooper black) – vacuum problem
- cleaning electrodes (enamel)
- active damping system in V-plane
- grooves – collaboration with SLAC



Stainless steel

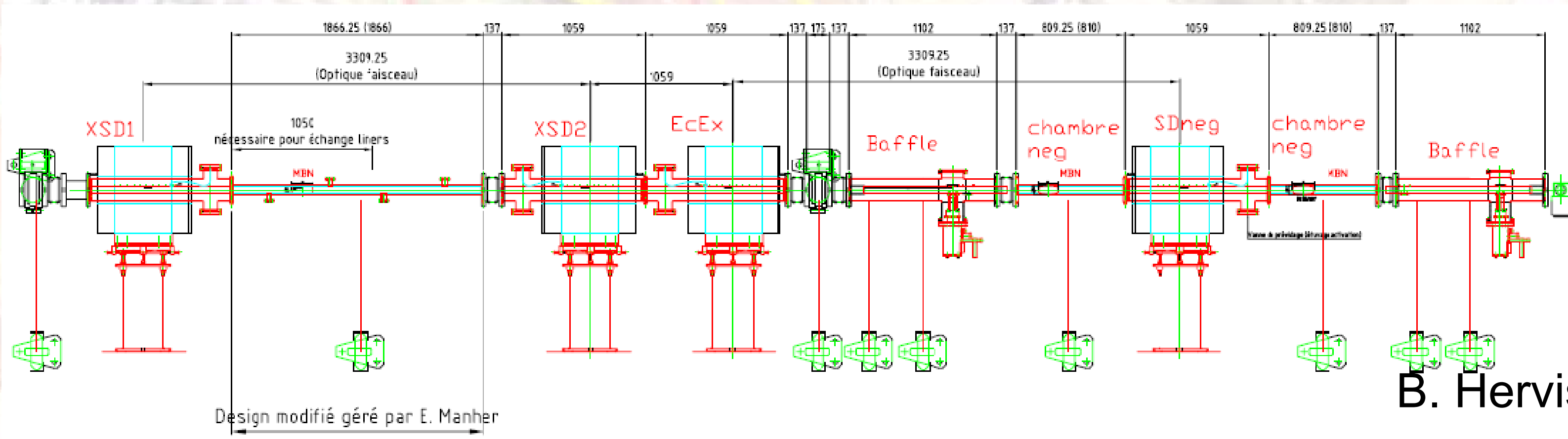


Carbon C-8



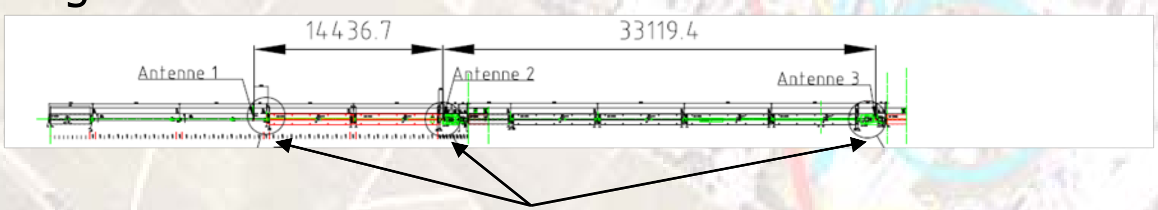
M. Taborelli

SPS upgrade: e-cloud mitigation
Experimental set-up in the SPS in 2008



B. Hervist

- 3 strip-line monitors XSD: st. steel for reference, new coating, NEG
- cleaning electrodes with button PUs



3 RF antennas for microwave measurements (at 2.8 GHz)

SPS upgrade: e-cloud mitigation. Possible vacuum chamber modification

S. Sgobba

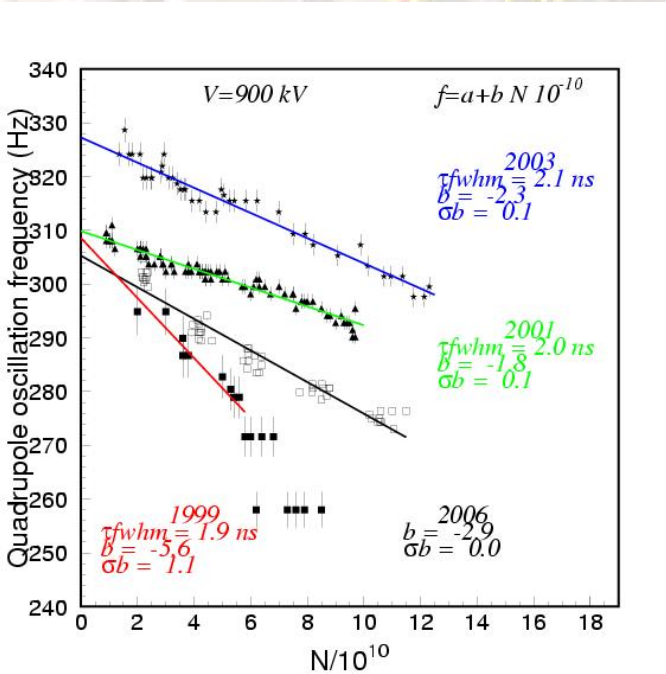
Implementation in the SPS tunnel

•Infrastructure partially exists due to ongoing refurbishing of the cooling circuits of dipoles (ECX5 cavern – cylinder of 20 m diameter)

•1000 vacuum chambers can be done in 3 years (during shutdown) → 4-5 chambers per day with 2 coating benches.

•LHC cold bore cleaning machine is also available if cleaning required

SPS limitations: impedance



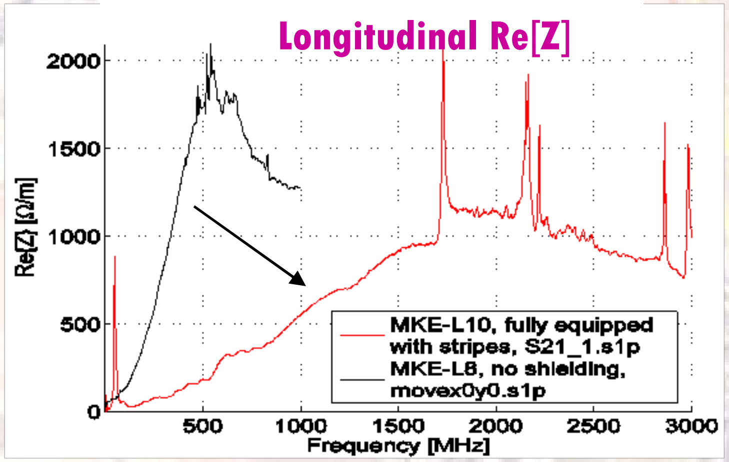
Quadrupole oscillation frequency as a function of bunch intensity

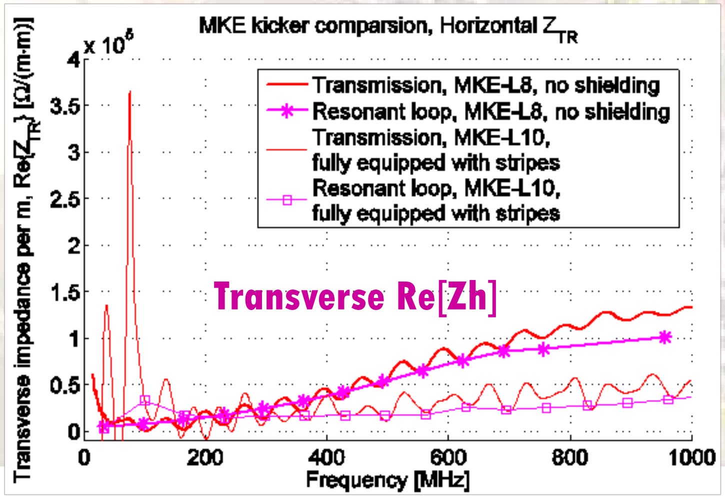
Im Z_{eff} ~ slope

Similar measurements in V-plane (H. Burkhardt et al.)

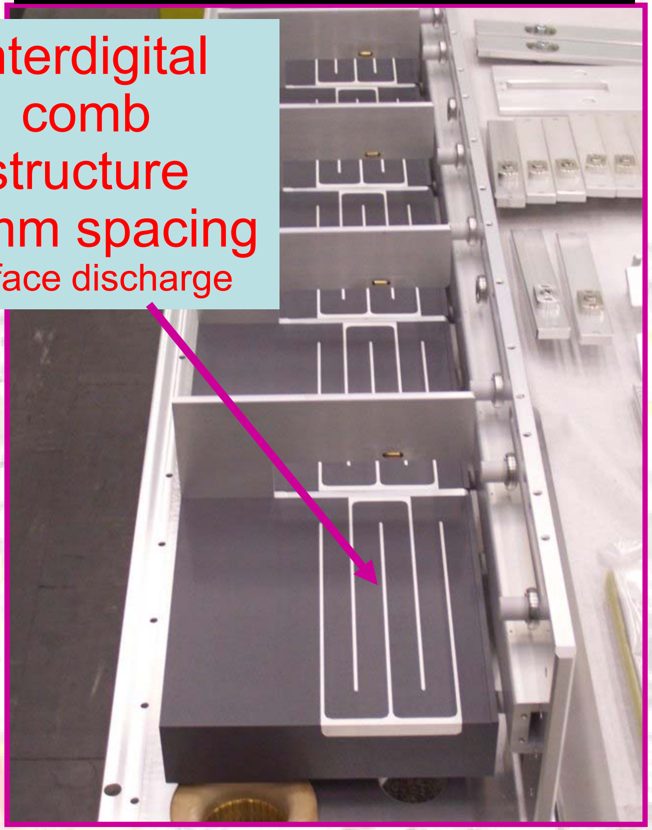
- 2001/2002: SPS impedance reduction in preparation for nominal LHC beam → no microwave instability
- 2003-2006: impedance increase, mainly due to re-installation of 9 MKE – extraction kickers for LHC
- Only 50% of SPS transverse impedance budget is known (E. Metral et al.) → search for the rest
- Shielding of the known impedance sources (MKE)

SPS limitations: impedance
MKE kicker shielding



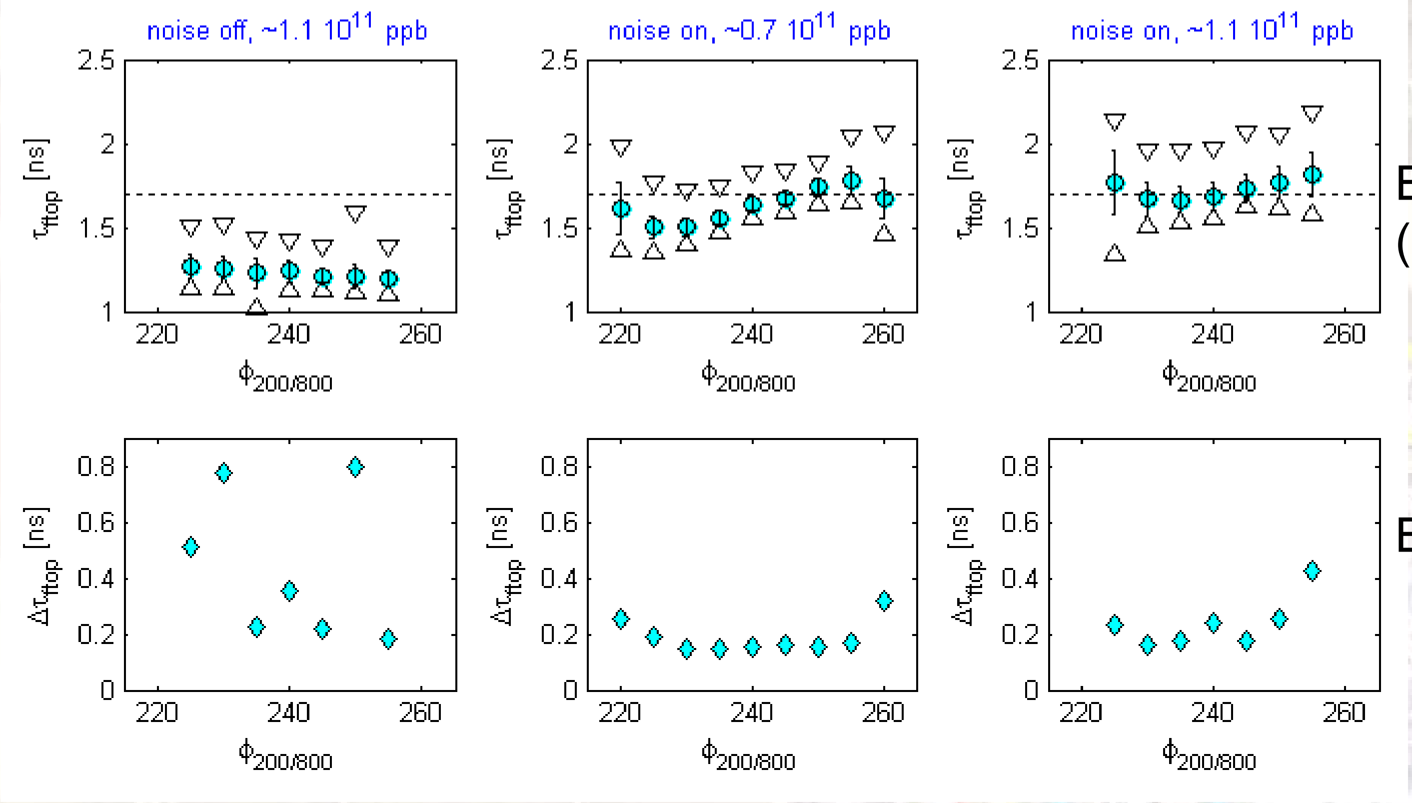


Printed strips in MKE-L10



F. Caspers, T. Kroyer et al.

SPS: coupled bunch instabilities



Bunch length (av., max-min)

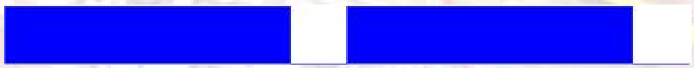
Beam stability

G. Papotti et al.

- **Present cures:** 800 MHz in bunch-shortening mode and controlled emittance blow-up → 0.9 eVs for upgrade intensities

SPS upgrade: potential for other (fixed target, CNGS) beams

with PS



←one PS cycle→|←one PS cycle→

with PS2

←one PS2 cycle (5-turn extract.) →

Main intensity limitations:

- beam losses (transition crossing, no bunch-to-bucket transfer)
- beam control
- RF voltage and power

Flux: 0.6 (1.0)x10^{20} pot/year for intensity of 6x10^{13} and 6 s cycle

Potential proton flux with maximum PS2 intensity for

- 200 days of operation,
- 80% beam availability,
- 45 (85)% beam sharing

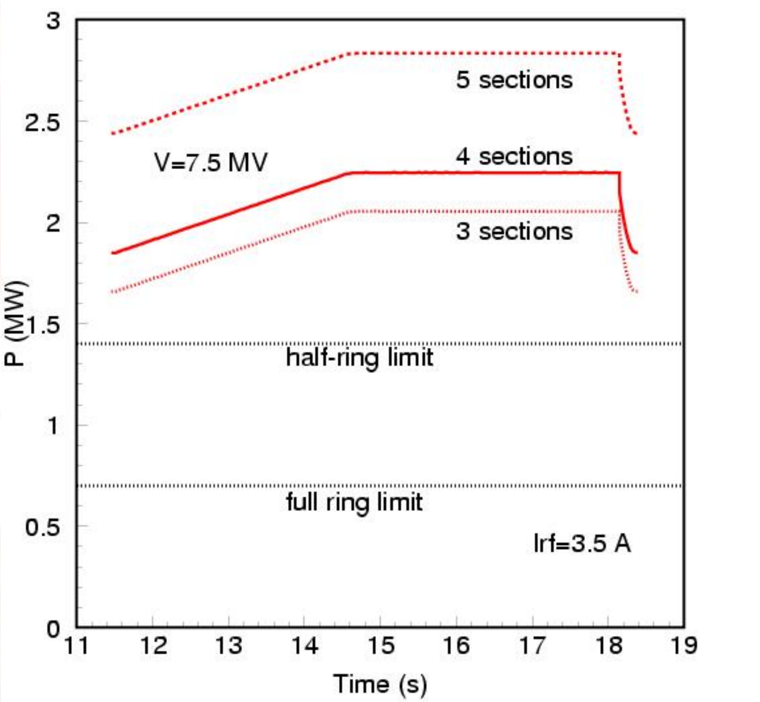
6.0 s cycle: 1.0 (2.0)x10^{20} pot/year
→ RF power upgrade

4.8 s cycle: 1.3 (2.5)x10^{20} pot/year
→ + new RF (voltage)

M. Meddahi, E.S., 2007

SPS: RF system upgrade

RF power for LHC upgrade intensity



- Threshold of coupled-bunch instabilities is decreasing during cycle with minimum on flat top
- Larger emittance needed for higher intensities ($\varepsilon \sim \sqrt{N}$)
- The 200 MHz RF system limits:
  - Voltage 7.5 MV
  - Power 0.7 MW for full ring
- (3.3-4.5) MW per cavity for max. PS2 intensity

→ The 200 MHz and 800 MHz power plant should be doubled

→ R&D for re-design of couplers and coaxial lines

→ Cavity length (200 MHz) could be optimised (5 → 3 sections)

Planning and milestones

- Linac4 project start: 2008; commissioning: 2012
- Beam from modified (2012/2013) PSBooster: May 2013
  → Shorter PS cycle and LHC filling time, ultimate LHC intensity, more beam for low energy physics

- Project proposal for LP-SPL, PS2 and SPSU: June 2011
- Project start: January 2012
- LP-SPL commissioning: mid-2015 – end-2016
- PS2 commissioning: mid-2016 – end-2016
- SPS commissioning: May 2017
- Nominal LHC beam for physics with new SPS injectors: July 2017
- Ultimate beam from SPS: 2018
- High intensity beam for physics: depends on the SPS upgrade
  → More reliable operation, shorter LHC filling time with higher intensity, high proton flux from LPSPL, PS2 and SPS
  → Potential for DLHC with SPS+ (new magnets 50 GeV → 1 TeV)

Summary

- The upgraded CERN injectors will produce high intensity beam with high reliability both for LHC and other users
- All machines in the LHC chain will be replaced by new ones except the SPS, which will profit from a higher injection energy
- The SPS upgrade is a key element for the LHC to benefit fully from new upstream machines
- New physics programmes requiring high beam power at a few GeV (e.g. neutrino and radioactive ion beam facilities) could later be possible by upgrading the LPSPL

First circulating beam in LHC foreseen on 10th September 2008

→ Time to think seriously about LHC upgrade!

Acknowledgments and references

- **Physics opportunities for Future Proton Accelerators (POFPA)** http://pofpa.web.cern.ch/pofpa/
- **Proton Accelerators for Future (PAF):** http://paf.web.cern.ch/paf/

  Members: R. Garoby (chairman), M. Benedikt, O. Bruning, M. Meddahi, R. Ostojic, E. S., M. Vretenar, F. Zimmermann
- **SPS Upgrade:**

  http://paf-spsu.web.cern.ch/paf-spsu/

  Members: G. Arduini, F. Caspers, S. Calatroni, P. Chiggiato, K. Cornelis, B. Henrist, E. Mahner, E. Metral, G. Rumolo, E. S., M. Taborelli, C. Yin Vallgren, F. Zimmermann

RF: T. Bohl, E. Ciapala, T. Linnecar, J. Tuckmantel, G. Papotti