SLHC-PP
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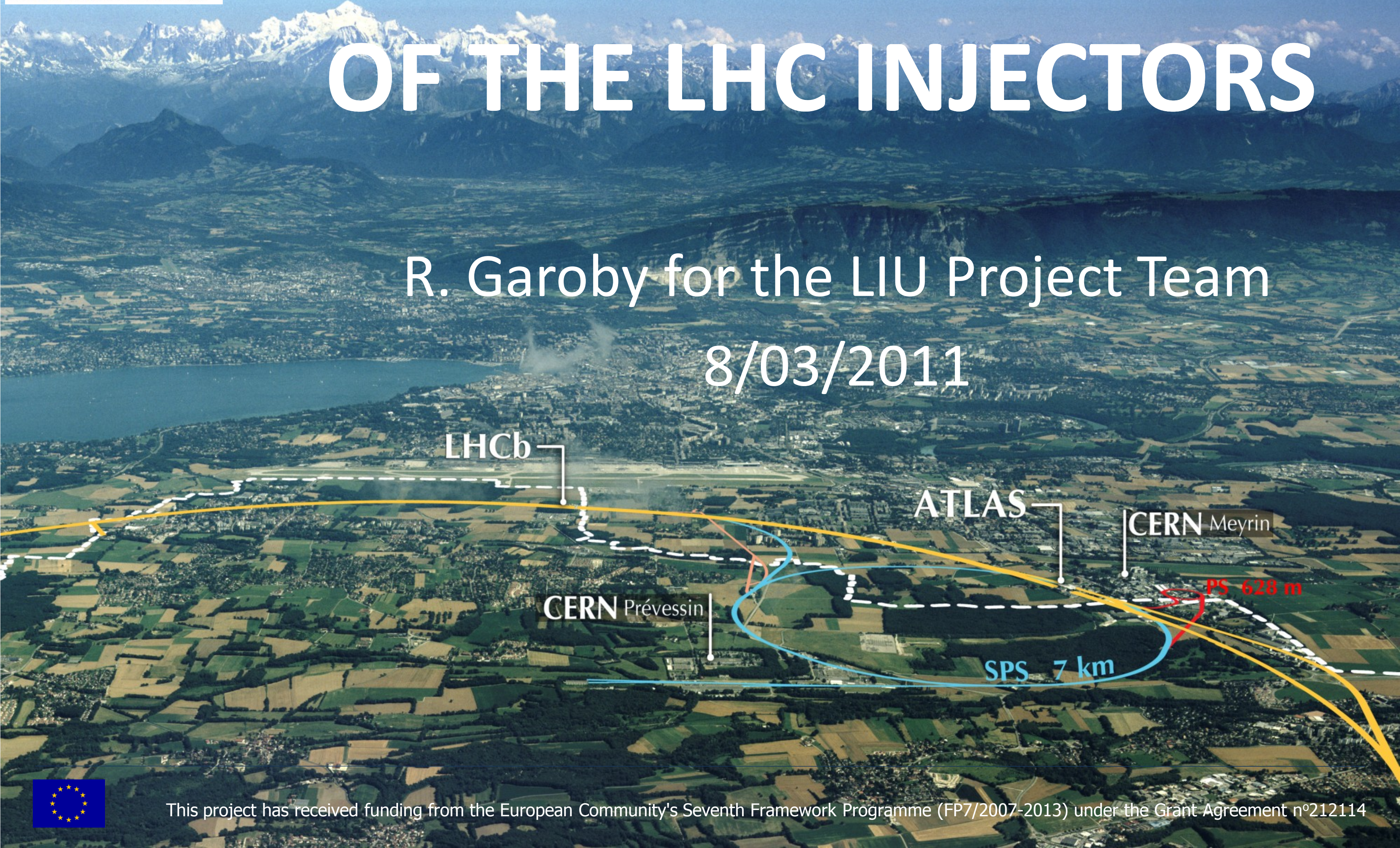
LARGE HADRON COLLIDER UPGRADE

PLANS FOR THE UPGRADE OF THE LHC INJECTORS

R. Garoby for the LIU Project Team

8/03/2011



This project has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under the Grant Agreement nº212114

Outline

- Introduction
- Needs of the “High Luminosity LHC”
- Plans for the injectors’upgrade
- Summary

Introduction

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CERN Scientific Strategy

http://cern.ch/SLHC-PP

Based on the experience gained diagnosing and repairing the LHC in 2008 and 2009 the following decisions have been taken in 2010 and formalized in the CERN Medium Term Plan 2011-2015:

⇒ **LHC will operate until ~2030. Experiments expect to accumulate ~3000 fb^{-1}.**

⇒ **During its last decade of operation, the LHC shall aim at a useful average luminosity of 5 10^{34} $cm^{-2}s^{-1}$.**

⇒ **The upgrade of the LHC itself for High Luminosity shall be implemented in ~2020,**

⇒ **The injectors shall be adapted to meet reliably the performance required by the High Luminosity LHC for as long as it operates (2030).**

Organization

http://cern.ch/SLHC-PP

- **Two projects have been created o**
  implementing the High Luminosity

WP2: Management tools
WP5: Radioprotection
WP6: NbTi Wide Aperture Quadrupole

⇒ **"HL-LHC" for the LHC itself**

"This new study combines all work related to the provision of a
luminosity of the LHC (i.e. 5×10^{34} cm^{-2}s^{-1}) and with an enhance

WP2: Management tools
WP5: Radioprotection
WP7.1: H^- ion source

⇒ **"LHC Injectors Upgrade" (LIU) for the injector complex**

"The LHC Injectors Upgrade should plan for delivering reliably to the LHC the beams required for reaching the goals of the HL-LHC. This includes LINAC4, the PS booster, the PS, the SPS, as well as the heavy ion chain."

- **R and D for a Super conducting Proton Linac is pursued as an option for future potential application**

WP7: H^- ion source § pulsed SC RF

Needs of the “High Luminosity LHC”

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Analysis

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Most important characteristics:

Integrated Luminosity = Luminosity x Time
(proportional to number of events)

$$\text{Luminosity} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot N_b \cdot k_b$$

with N_b : number of protons/bunch
$\varepsilon_{X,Y}$: normalized transverse emittances
k_b : number of bunches per ring

Time: Duration of data taking

⇒ **LHC requirements on its injectors**

Detailed specifications to be established with HL-LHC Project

($N_b/\varepsilon_{X,Y}$ is called "beam brightness")

➢ **Consequence for the injectors**

⇒ **The LHC imposed brightness must be present from the lowest energy because brightness is (at best) conserved in a cascade of proton accelerators (Liouville's theorem).**

$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

with N_b : number of protons/bunch
$\varepsilon_{X,Y}$: normalized transverse emittances
R : mean radius of the accelerator
$\beta\gamma$: classical relativistic parameters

⇒ **Severe constraint at low energy because of space charge tune spread ΔQ_{SC}**

⇒ **Need for high availability (reliability) and flexibility**

HL-LHC beam characteristics

Scenarios for increasing the LHC luminosity

(Preliminary but typical!)

- Nominal luminosity (10^{34} $cm^{-2}s^{-1}$) reached with:
  - **75 ns spacing, 1.7 10^{11} p/b, emittances = 2.7 μrad, β*=0.55 m**
  - **or 50 ns spacing, 1.7 10^{11} p/b, nominal emittances (3.75 μrad), β*=0.55 m**
- 2 x nominal luminosity reached with:
  - **50 ns spacing, 2.3 10^{11} p/b, nominal emittances, β*=0.55 m**
  - **or 25 ns spacing, 1.15 10^{11} p/b, emittances = 1.9 μrad, β*=0.55 m**
- 3 x nominal luminosity reached with:
  - **25 ns spacing, 1.7 10^{11} p/b, emittances = 2.7 μrad, β*=0.55 m**
- 6 x nominal luminosity reached with:
  - **25 ns spacing, 1.7 10^{11} p/b, emittances = 1.9 μrad, β*=0.3 m**

Comparison with present injectors performance

http://cern.ch/SLHC-PP

From R. Steerenberg

	Expected Beam Characteristics at SPS exit in 2011				HL-LHC (tentative) requirements		
	Ip / bunch [x10^{11}]	ε_h and ε_v [mm · mrad] 1σ, norm.	ε_{longit} [eVs]	nb bunches	Ip / bunch [x10^{11}]	ε_h and ε_v [mm · mrad] 1σ, norm.	Peak Luminosity [x10^{34} $cm^{-2}s^{-1}$]
LHC25 (DB)	1.15	3.6	0.7	1 - 4 x 72	1.7	1.9	6 (β*=0.3 m)
LHC50 (SB)	1.45	3.5	≤ 0.8	1 - 4 x 36	2.3	3.5	2 (β*=0.55 m)
LHC50 (DB)	1.15 (?)	1.5 (?)	≤ 0.8	1 - 4 x 36			
LHC75 (SB)	1.2	2	≤ 0.8	1 - 4 x 24	1.7	2.7	1 (β*=0.55 m)
LHC75 (DB)	1.2 (?)	1 (?)	≤ 0.8	1 – 4 x 24			
LHC150 (SB)	1.1	< 2.5 (1.6)	≤ 0.8	1 - 4 x 12			

Final requirements will depend upon experience with LHC and progress with technological developments. Clear trends:

- Intensity per bunch ≥ ultimate (1.7 10^{11} p/b)
- Transverse emittances << nominal (3.75 mm.mrad)
- Interesting potential of 50 ns bunch spacing, but likely preference for 25 ns for highest luminosity (except if strong limitation e.g. because of e-clouds)

Plans for the Injectors' Upgrade

Goals § Means

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To increase performance

Brightness ↗

⇒ **Increase injection energy in the PSB from 50 to 160 MeV, Linac4 (160 MeV H^-) to replace Linac2 (50 MeV H^+)**

⇒ **Increase injection energy in the PS from 1.4 to 2 GeV, increasing the field in the PSB magnets, replacing power supply and changing transfer equipment**

⇒ **Upgrade the PSB , PS and SPS to make them capable to accelerate and manipulate a higher brightness beam (feedbacks, cures against electron clouds, hardware modifications to reduce impedance…)**

To increase reliability and lifetime (until ~2030!)

(tightly interleaved with consolidation)

⇒ **Upgrade/replace ageing equipment (power supplies, magnets, RF…)**

⇒ **Procure spares**

⇒ **Improve radioprotection measures (shielding, ventilation…)**

Linac4 [1/6]

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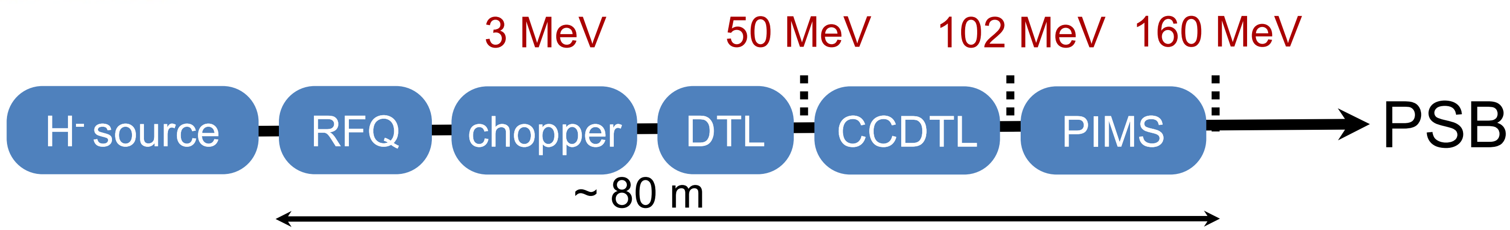

Ion species	H^-
Output Energy	160 MeV
Bunch Frequency	352.2 MHz
Max. Rep. Rate	2 Hz
Max. Beam Pulse Length	1.2 ms
Max. Beam Duty Cycle	0.24 %
Chopper Beam-on Factor	65 %
Chopping scheme: 222 transmitted /133 empty buckets	
Source current	80 mA
RFQ output current	70 mA
Linac pulse current	40 mA
N. particles per pulse	1.0×10^{14}
Transverse emittance	0.4 π mm mrad

H^- charge exchange injection in the PSB

160/50 MeV $\Rightarrow$ factor 2 in $\beta\gamma^2$) $\rightarrow$ doubled brightness in the PSB

Chopping at low energy to ease longitudinal capture and reduce beam loss in PSB.

Linac4 [2/6]

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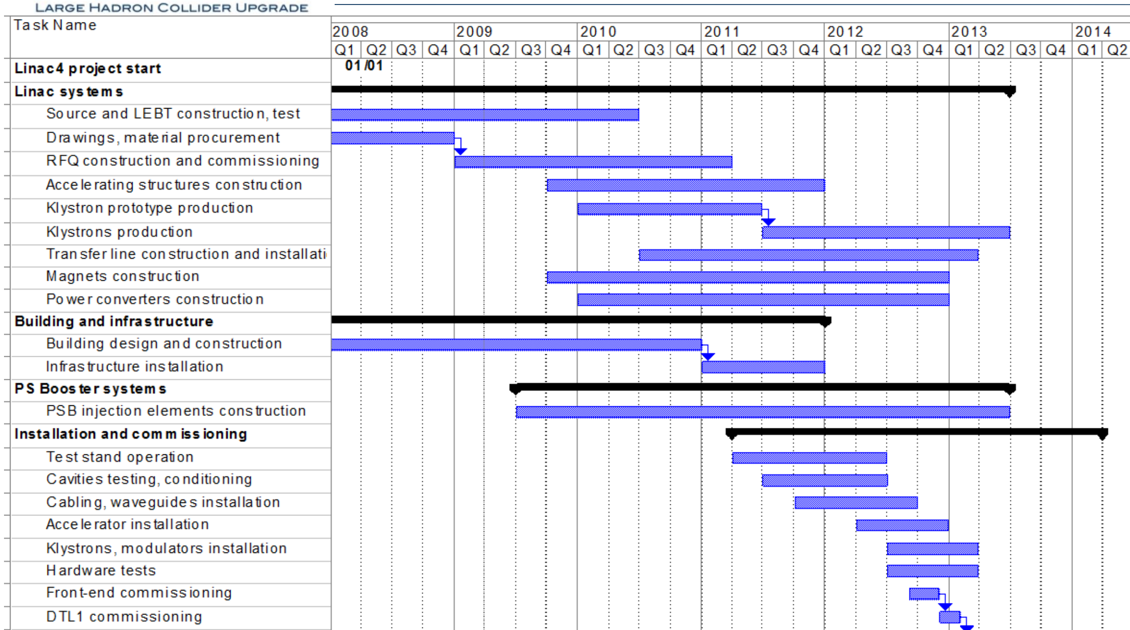
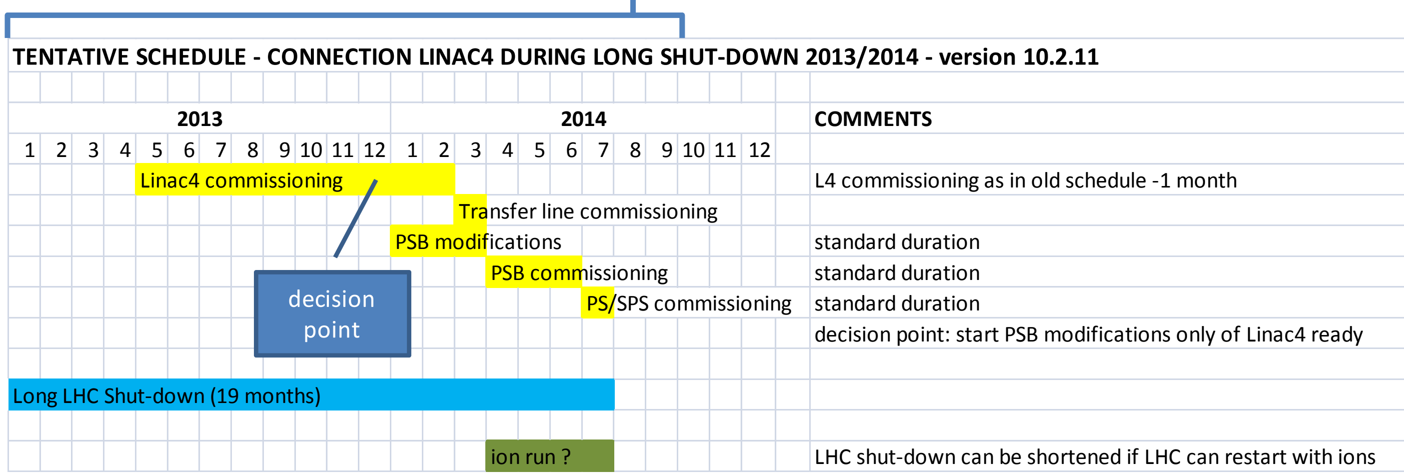


Milestones

- End CE works: December 2010
- Infrastructure: 2011
- Installation: 2011-2012
- Commissioning: 2013 till Q1-2014
- Modifications PSB: Q1-2014
- **PSB commissioning: Q2-2014**
- **Operation: Q3-2014**



Linac4 [3/6]

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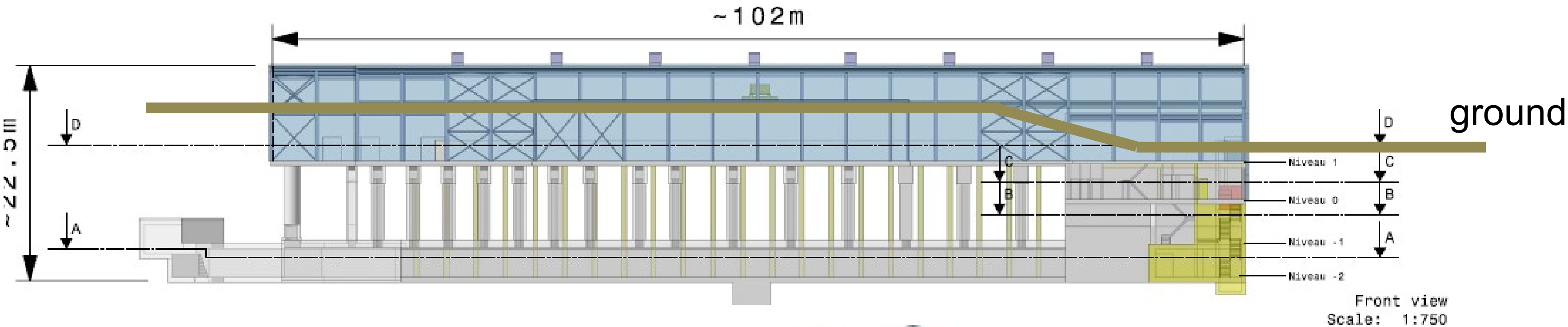
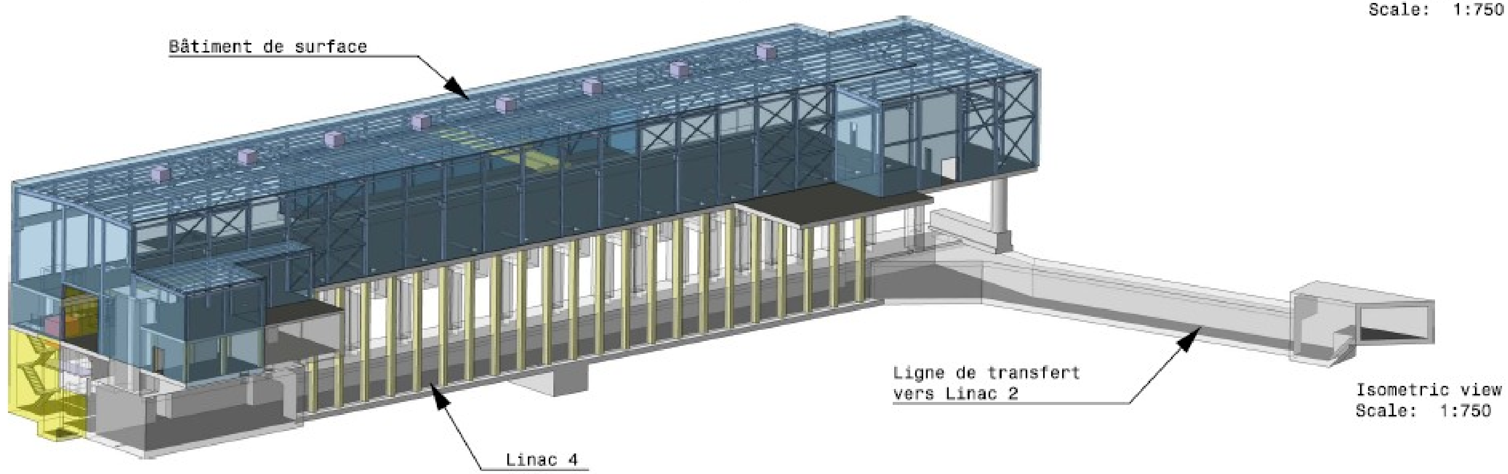
Building completion in October 2010

Linac4 [4/6]

Building completion in October 2010

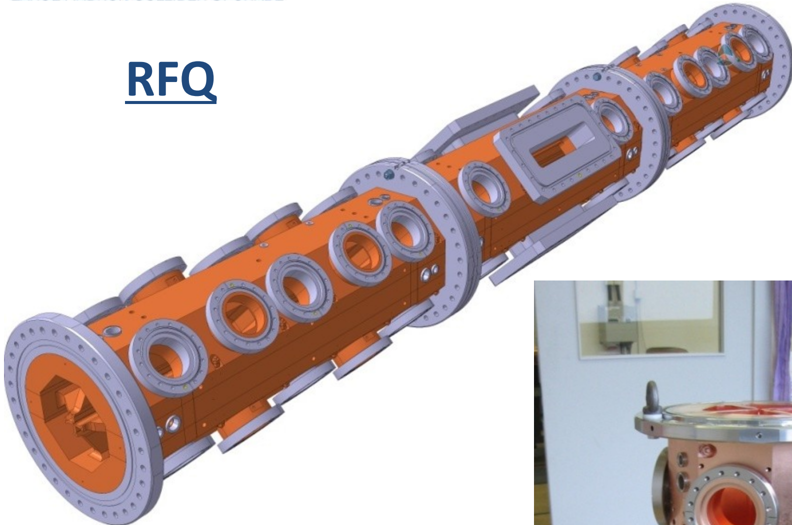


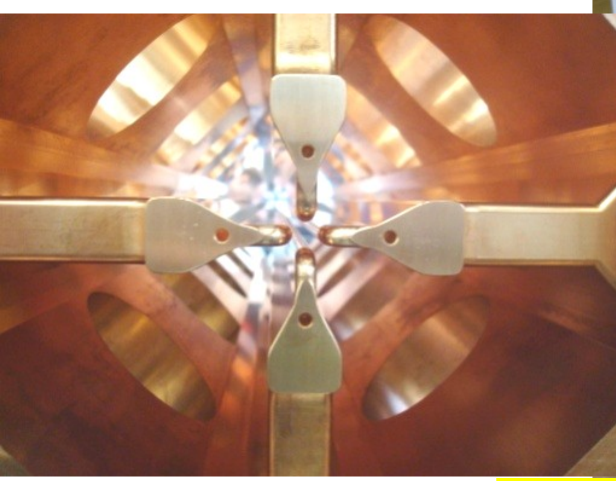


- Design of building started in December 2006.
- Overall floor surface of Linac4 installations = 3’305 m2 (over 4 levels)
- Completion in October 2010

Linac4 [5/6]

RFQ





module #1

Energy **3 MeV** (below radiation threshold)
Length **3m**, 3 section of 1 m each.

Brazed 4-vane design. Simplified shape and cooling (max. duty of 10%).

Collaboration with CEA Saclay (in charge of thermal simulations and of RF design, measurement and tuning).

Construction entirely done at CERN: machining, metrology, brazing (horizontal).

Status: Module #1 completed (2 brazing steps), Module #2 ready for brazing, Module #3 under machining.

RFQ ready for RF tests in June 2011.

Linac4 [6/6]

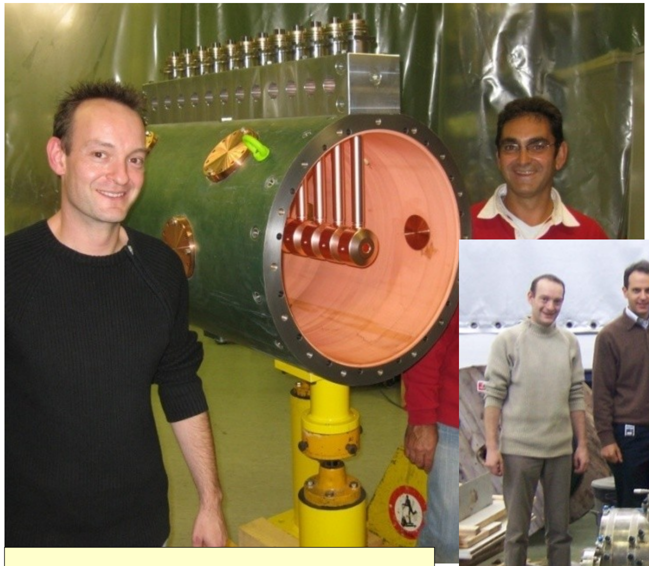
Accelerating structures

Three structures of new design:

DTL (Drift Tube Linac): complete revision of mechanical design w.r.t. other projects.

CCDTL (Cell-Coupled DTL): new structure, first time used in an accelerator.

PIMS (Pi-Mode Structure): new structure, first time used in a proton machine.



DTL prototype, 2009

CCDTL prototype, 2008

PIMS prototype, 2010

R&D since 2003.

Prototypes built (and tested at high RF power) for the three structures.

Construction starting in 2010.

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PSB Energy Increase § Consolidation [1/3]

http://cern.ch/SLHC-PP

From K. Hanke

Outcome of the Task Force created after the LHC Workshop in 2010 for studying and costing the increase of the PSB to PS transfer energy above 1.4 GeV.

Task Force members

CERN
CH-1211 Geneva 23
Switzerland

PSB 2.0

The
PSB Upgrade
Working Group

PSB Upgrade Working Group Document No.	1082646-0003
CERN Div./Group or Supplier/Contractor Document No.	BE-OP
EDMS Document No.	**1082646 v.3**

DATE: 2010-09-23

Feasibility Study

PS BOOSTER ENERGY UPGRADE FEASIBILITY STUDY FIRST REPORT

Abstract

This document summarises a survey of the CERN PS Booster systems with regard to a possible energy upgrade to 2 GeV. Technical solutions are proposed along with a preliminary estimate of the required resources and the time lines.

Prepared by:	*Checked by:*	*Approved by:*
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document released

PSB Energy Increase § Consolidation [2/3]

http://cern.ch/SLHC-PP

From K. Hanke

Subjects

(material cost in kCHF)

Magnets	3445
Magnetic Measurements	111
RF (High power and Low Level)	14320
Beam Intercepting Devices	700
Power Converters	21100
Vacuum System	100
Beam Instrumentation	67
Commissioning	50
Extraction, Transfer, Injection	5763
Controls	116
Electrical Systems	1700
Cooling & Ventilation	5500
Radio-Protection	0
Transport and Handling	680
Survey	50
Total Project	**53702**

PSB Energy Increase § Consolidation [3/3]

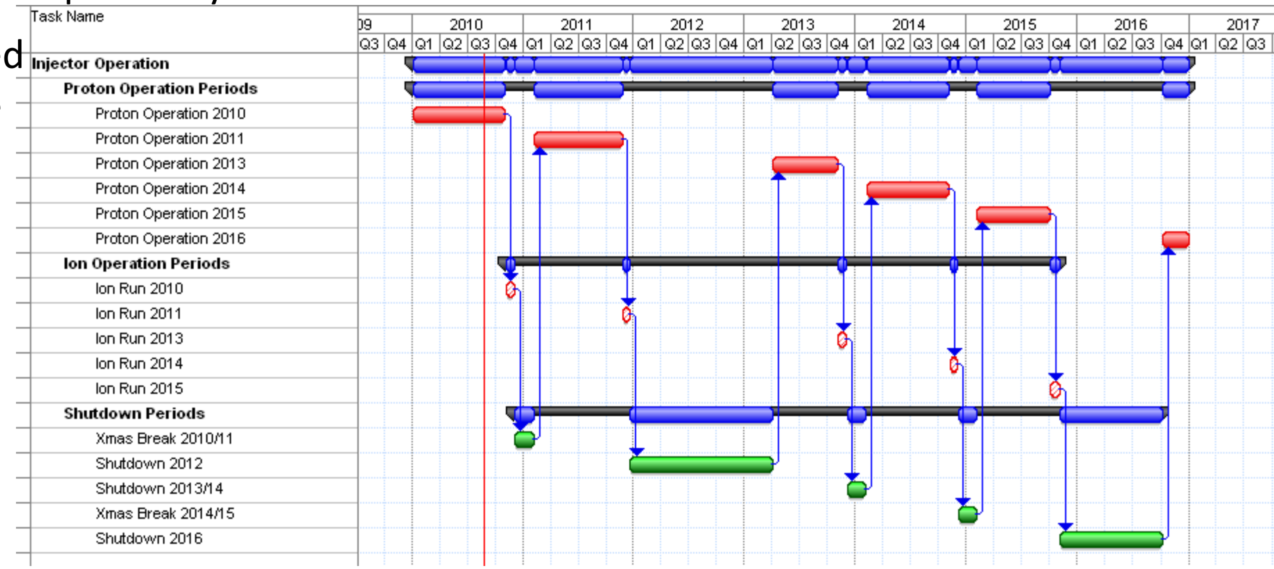
http://cern.ch/SLHC-PP

From K. Hanke

- one year of intense work
- different options studied; baseline scenario chosen
- an upgrade of the PSB from 1.4 GeV to 2.0 GeV is technically feasible
- a realistic estimate of budget and time lines has been made; the upgrade can be completed by 2016

Estimated total cost: 53.752 MCHF
(Consolidation: 27.320 MCHF Upgrade: 26.432 MCHF)

- the budget has been entered in the MTP according to the estimate (consol. and upgrade)
- ready for preparing TDR, pending evaluation of alternative scenarios and management decision



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RCS option

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C. Carli

Tentative RCS parameters

Energy range	160 MeV to 2 GeV
Circumference	(200/7) π m ≈ 89.76 m
Repetition rate	~10 Hz
RF voltage	60 kV
Harmonics	h…
Frequency range	
Beam parameters f… (for lower … do…	…determined by …es)
Lat…	…s and 3 periods, …rc, straight with one cell
Tunes	4 < $Q_{H,V}$ < 5
Relativis… …on	~4
Bending r… …ing factor	56 %
Maximum … …etic field	1.16 T

Benefits:

- Competitive cost wrt PSB consolidation and upgrade (?)
- Reliability (new hardware / modern design)
- Commissioning decoupled from physics operation
- Limited risk: Linac2 + PSB can remain available for a few years as back-up.

PS Upgrade Needs

From S. Gilardoni

Issues:

- Hardware for injection at 2 GeV: studied by the Task Force on «PSB energy upgrade » ⇒ preliminary solutions found
- Blow-up and instabilities in the transverse phase planes:
  - Dilution after injection oscillations due to mis-steering
  - Laslett tune shift due to space charge (even if < |0.3|)
    → Blow-up of first batch waiting for the second batch injection
  - Head-tail instability at low energy
  - TMCI close to transition
  - e-clouds effects on high energy flat-top
- Blow-up and instabilities in the longitudinal phase plane:
  - Transient beam loading effects especially at low voltage during gymnastics
  - Coupled bunch instabilities due to cavities impedances (reminder: 5 different RF systems in the PS for a total of 22 cavities)

PS Upgrades

[non-RF]

System	Elements	Impact	Comments
Injection elements	Injection septum Injection bumpers Eventual extra kicker	High	2 GeV operation. Promising design exists already. Includes power converters, magnets and control system.
Low energy correctors	100 horizontal correctors 30 vertical correctors	Low	2 GeV operation. Will be tested in MDs. Includes power converters, magnets and control system.
Low energy skew quadrupoles	45 magnets	High	2 GeV operation. Will be tested in MDs Used to damp HEADTAIL instability. Includes power converters, magnets and control system.
Low energy quadrupoles	40 magnets	Low	2 GeV operation. Will be tested in MDs. Includes power converters and magnets and control system. PFW could be used.
Transverse damper	Power part of existing system	Medium	Would be necessary if too large ripple of injection kicker. Used also to damp the HEADTAIL instability.
e-cloud attenuation system	Chamber coating or electrode Installation	Not clear yet	Studies to asses if limiting factor or not. Includes new e-cloud detectors.
Instrumentation	BWS, BCT, Orbit system, profile monitors.	Not clear yet	Revise the current performances to tests if comply with upgraded LHC beams.
Improved shielding on top of route Goward and on top of SMH16	Shielding elements		Required for PS non-LHC operation. Needed also for 1.4 GeV operation.

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PS RF Upgrades

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Priority	Item	When
[1]	New coupled-bunch FB	2012
2	Dedicated kicker cavity	2015-2020
10 MHz		
[1]	1-turn delay FB	2011
1	Renovate FB amplifiers	2011-2015 (?)
1	Slow phase loops around each cavity	2013-2014
2	New power amplifier (1 tube/gap)	2014-2018 (?)
20 MHz		
1	1-turn delay FB	2012
2	Slow phase loops around each cavity	2012
40 MHz		
[1]	Automatic tuning system	2011
1	1-turn delay FB	2012
2	New feedback amplifier in grooves	2014
2	Slow phase loops around each cavity	2012
3	Study more voltage per cavity	2013
3	New power supplies	2014-
80 MHz		
1	1-turn delay FB	2012
1	Automatic tuning system - PLC, prot./ions switching	2011-2012
2	Slow phase loops around each cavity	2012
2	New feedback amplifier in grooves	2014
2	Fast ferrite tuner	2016
3	Study more voltage per cavity	2013
3	New power supplies	2014-
3	Extra 80 MHz cavity	???

- Crude planning. Some items may only be implemented after 2017.
- Ongoing work is indicated with a bracket on priorities.
- Priorities may change depending upon the outcome of the studies

PS Performance Potential

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From S. Gilardoni

- Preliminary extrapolations with Linac4

Intensity PS ej. (ppb)	Bunch spacing	$\varepsilon_{(x,y)}$ PS ej. (1 σ norm) **no blow-up**	Laslett ΔQx	Laslett ΔQy	ε_l @ PSB	PSB int. per ring **(assuming 5-10% losses)**	Comment	
$3.0 \cdot 10^{11}$	25 ns (DB)	2.5 μm rad	-0.24	-0.37	< 2 eVs (160 ns)	~ $400 \cdot 10^{10}$	Optimistic from Low εL	Stretched
$1.5 \cdot 10^{11}$	25 ns (SB)	2.5 μm rad	-0.18	-0.28	1.4 eVs (120 ns)		Limited by L4 brightness	
$1.9 \cdot 10^{11}$	25 ns (DB)	2.5 μm rad	-0.14	-0.22	< 2 eVs (160 ns)	~ $240 \cdot 10^{10}$	Pessimistic lower limit	Realistic
$3.0 \cdot 10^{11}$	50 ns (DB)	2.5 μm rad	-0.11	-0.17	< 2 eVs (160 ns)	~ $190 \cdot 10^{10}$	Optimistic from Low εL	Stretched
$1.9 \cdot 10^{11}$	50 ns (DB)	2.5 μm rad	-0.07	-0.11	< 2 eVs (160 ns)	~ $125 \cdot 10^{10}$	Pessimistic lower limit	Realistic
$1.7 \cdot 10^{11}$	25 ns (DB)	1.5 μm rad	-0.3	-0.3	< 2 eVs (160 ns)	~ $220 \cdot 10^{10}$	Minimum $\varepsilon_{(x,y)}$	
$2 \cdot 10^{11}$	25 ns (DB)	1.8 μm rad	-0.3	-0.3	< 2 eVs (160 ns)	~ $250 \cdot 10^{10}$	Minimum $\varepsilon_{(x,y)}$	
$2.7 \cdot 10^{11}$	50 ns (DB)	1.1 μm rad	-0.3	-0.3	< 2 eVs (160 ns)	~ $170 \cdot 10^{10}$	Minimum $\varepsilon_{(x,y)}$	Stretched

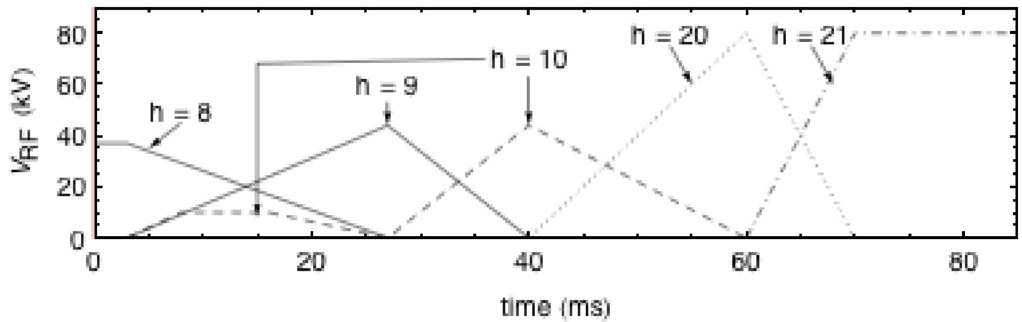
- Need further studies and MDs to improve these estimates:
  - Longitudinal phase plane: impact of beam loading and possible cures,
  - Transverse phase planes: blow-up rate with high space charge, e-clouds effects
  - Radio protection (especially if other users attempt to profit from a higher PS intensity)
  - Specifications of feedbacks and analysis of feasibility

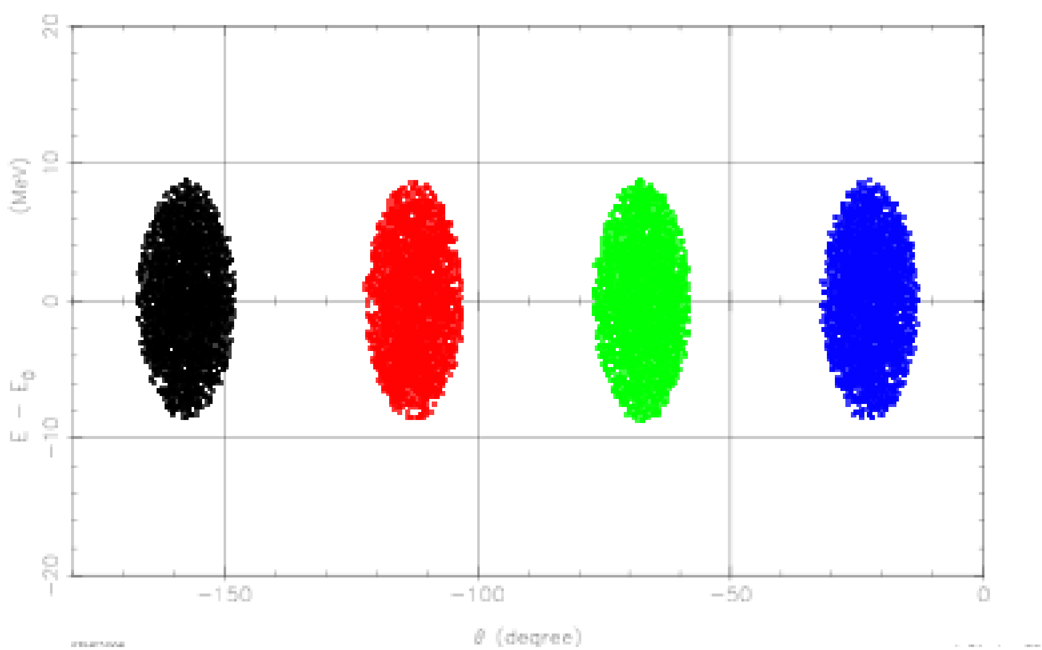
PS Gymnastics Upgrade

From C. Carli

Alternative RF gymnastics using all PSB rings

- Scheme yielding 64 bunch
  - Brightness increase: 1
  - Reasonable complexit
- Scheme yielding 48 bunch
  - Brightness increase cc
  - Complex RF gymnasti steps
- Any compression scheme energy upgrade
- Tests can proceed immedi from the PSB at 1.4 GeV a ultimate 25 ns bunch trair 2012 (although at the cost efforts from the PS LLRF te





Status of SPS Studies

E. Shaposhnikova

Main lessons/results from 2010

- Nominal 25 ns beam in good shape: low beam losses (5%) even with low $\xi_v = 0.1$
- Ultimate (injected) beam - needs studies
  - 25 ns: large losses and emittances, instabilities
  - 50 ns: 15% losses, $1.5\text{x}10^{11}$/bunch at 450 GeV/c in 4 batches
- TMCI threshold is at ultimate intensity (low ξ). Ultimate single bunch accelerated to 450 GeV/c with low loss and ξ_v, but with some emittance blow-up. More problems for small injected emittances.
- New low γ_t optics: promising results for beam stability and brightness
- Limitations for dedicated LHC filling/MD: MKE, MKP, MKDH3 heating/outgassing
- MDs issues: transverse emittance measurements, time allocation, data analysis

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Electron clouds in the SPS

http://cern.ch/SLHC-PP

J.M. Jimenez

High bunch intensity, and/or Small emittances (LHC requirements) are impossible in the SPS at **short bunch spacing** because of electron clouds generating:

- *pressure rise*: beam gas scattering, dose rates to tunnel and components
- *beam instabilities*: transverse emittance blow-up and single bunch vertical instability

Possible actions

- Suppression: Clearing electrodes
  - Aperture, impedance, full-scale feasibility, lifetime, quads, LSS, cabling, powering, etc.
- Mitigations
  - a-C coatings
    - Lifetime, stability with venting, outgassing rates, in-situ coating, LSS.
  - Scrubbing runs
    - Feasibility and margin, MD time
- (Potential) Cure
  - Wide band feedback systems
    - High speed digitization and digital treatment
- Simulations
  - e-cloud budget, stability expected, emittance growth, impedance from electrodes, effectiveness of wide band feedback, etc.
  - *If we rely on beam scrubbing in the LHC why not in the SPS?*

SPS Hardware Upgrades

http://cern.ch/SLHC-PP

B. Goddard

Baseline for LIU-SPS

- RF 200 MHz upgrade: completed for 2018
- ecloud mitigation: aC coating, 1 sextant LS1, completed for 2018
- New high bandwidth damper: completed for 2016
- Existing damper power upgrade: completed for 2014
- Beam instrumentation upgrade : completed for 2014
- Scraper upgrade: completed for 2014
- Extraction and TL protection upgrade: completed for 2015
- MKE impedance reduction: completed for 2012
- MKDV/H impedance reduction (transitions): completed for 2014

- Beam dump design study: completed by end 2013
- New MKE design study: completed by end 2013

SPS Performance Potential

http://cern.ch/SLHC-PP

E. Shaposhnikova

SPS Q&A

- **Intensity per bunch and emittance as a function of the distance between bunches today and after upgrade?**

  - before upgrades, single-bunch performance can probably be achieved with 50 & 75 ns beams (~3 μm emittances at ultimate intensity); hopefully less (2.5 μm ?) with low γ_t (RF voltage limit to be seen); > 4 μm for 25 ns (ultimate beam)
  - after upgrades (200 MHz RF upgrade, e-cloud mitigation/cure, transverse impedance reduction, upgraded transverse feedback, etc.) the space charge limit could be attained (~2.5 μm with ultimate intensity for 50&25 ns beams)

- **What should be done for delivering smaller transverse emittances at ultimate current?**

  - more MDs with PS beams of very small transverse emittances
  - need for improved beam instrumentation (trans. emittance measurement)
  - low γ_t optics ?

Summary

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LARGE HADRON COLLIDER UPGRADE

Draft Planning

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	Linac4	PS injector, PS and SPS	Beam characteristics at LHC injection
2011 - 2012	Continuation of construction…	• Beam studi • Investigatio • Hardware p • Design § construction of some equipment • TDR	25 ns, 1.15 10^{11}p/b, 3.5 mm.mrad 50 ns, 1.7 10^{11}p/b, ≤3.5 mm.mrad 75 ns, 1.2 10^{11} p/b, ≤ 2 mm.mrad
2013 – Q2/2014 (Long Shutdown 1)	• Linac4 beam commissioning • Connection to PSB	• PSB modification (H^- injection) • PSB beam commissioning • Modifications and installation of prototypes in PS and SPS	
Q3/2014 - 2016	• Progressive increase of Linac4 beam current • Progressive increase of PSB beam brightness	• Beam studies • Equipment design § construction	• Improved beam from PSB • Some improvement of PS beam • Little gain for the SPS (pending SPS hardware upgrades)
2017 – Qx/2018 (Long Shutdown 2)		• Installation in PS and SPS • Beam commissioning	
Qy/2018 –2020			After ~1 year: All beam characteristics expected for the HL-LHC…

SPS limitation

PS limitation

Conclusions

- **Experience with beam in the LHC in 2011-2012 will help refine the beam characteristics required for HL-LHC.**
- **Experience with beam in the injectors in 2011-2012 will help determine the precise upgrades required.**
- **The SPS remains the limiting accelerator in the injector chain. The well-identified improvements shall be implemented as soon as possible to allow studying the other limitations.**
- **The possibility to connect Linac4 to the PSB during the first long shutdown is worth being investigated, as well as the option to replace the PSB with an RCS.**

THANK YOU FOR YOUR ATTENTION!