CERN
European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

LHC Injectors Upgrade (LIU) Project

OUTLINE

- ✓ New Scientific Strategy of CERN
- ✓ Needs of the “High Luminosity LHC”
- ✓ Plans for the Injectors’ Upgrades

R. Garoby

8/02/2011

New Scientific Strategy (1/2)

- **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 Medium Term Plan 2011-2016:**

⇒ **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} Hz/cm^2.**

⇒ **The High Luminosity upgrade of the LHC itself (new IRs with new magnets) shall be implemented a few years before 2020,**

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

⇒ **The baseline solution for the injectors is to consolidate and upgrade the existing accelerators (including Linac4) and the construction of new injectors (LP-SPL + PS2) is a back-up plan:**

  ⇒ **Linac4 will replace Linac2**
  ⇒ **The PSB to PS transfer energy shall be increased**
  ⇒ **The SPS is a bottleneck which deserves intense work**
  ⇒ **Extensive consolidation is mandatory**

New Scientific Strategy (2/2)

- **Two projects have been created on January 1, 2011 for studying and implementing the High Luminosity Upgrade:**

⇒ **"HL-LHC" for the LHC itself (Project Leader: L. Rossi)**

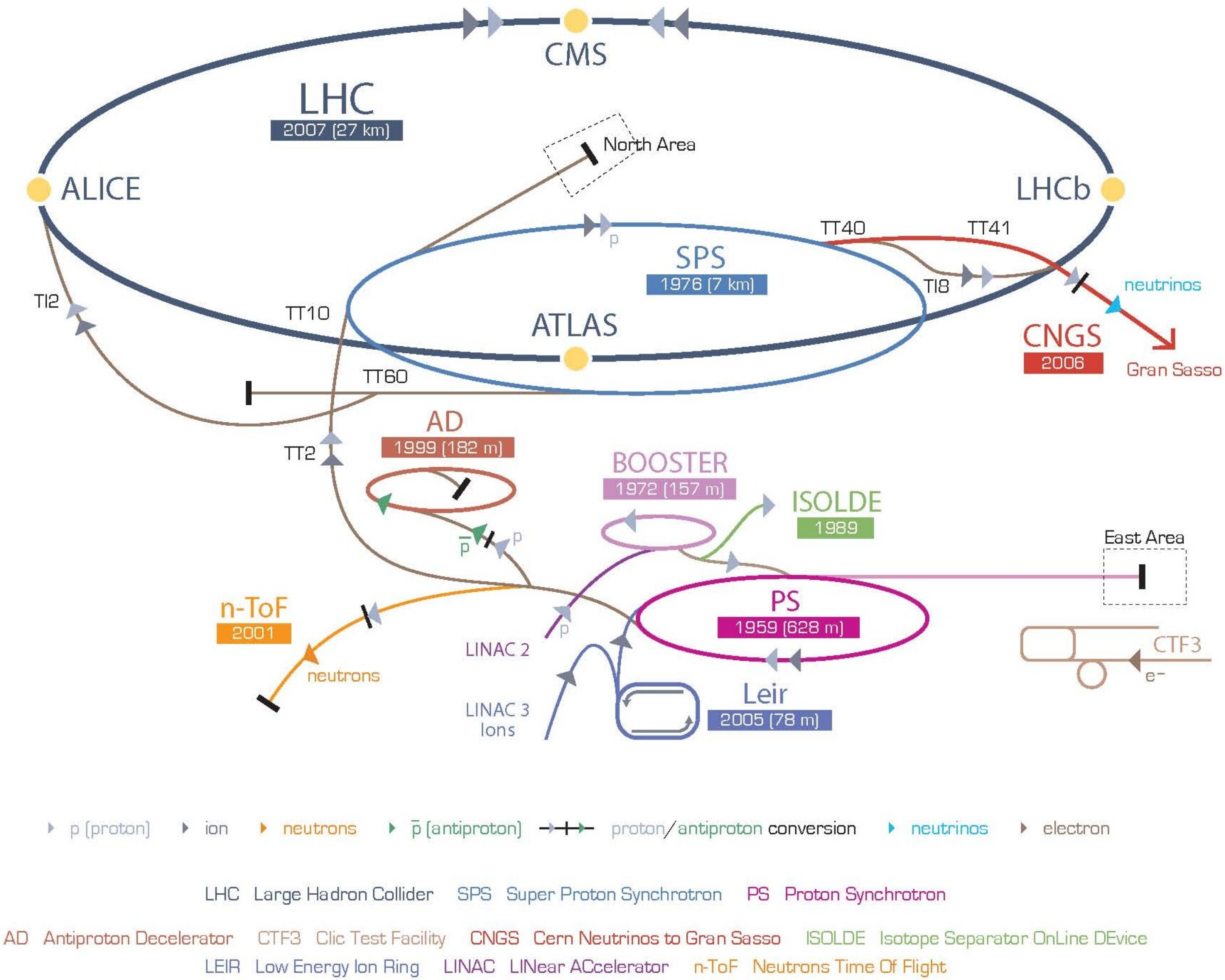
"This new study combines all work related to the provision of a peak luminosity of five times the design luminosity of the LHC (i.e. 5×10^{34} $cm^{-2}s^{-1}$) and with an enhanced luminosity lifetime by "luminosity leveling"".

⇒ **"LHC Injectors Upgrade" (LIU) for the injectors (Project Leader: R. Garoby)**

"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 in view of a potential proton driver for a neutrino facility**

The LHC Injector Complex



Needs of HL-LHC (1/3)

- **Most important parameters:**

  Luminosity

  (proportional to the number of events per second)

  + maximum duration of data taking

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

with N_b : number of protons/bunch

$\varepsilon_{X,Y}$: normalized transverse emittances

k_b : number of bunches per ring

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

- **LHC requirements on its injectors**

Detailed specifications to be given by HL-LHC Project

- **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).**

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

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

with N_b : number of protons/bunch

$\varepsilon_{X,Y}$: normalized transverse emittances

R : mean radius of the accelerator

$\beta\gamma$: classical relativistic parameters

+ high reliability and flexibility

Needs of HL-LHC (2/3)

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**

Needs of HL-LHC (3/3)

From R. Steerenberg

Peak Performances !!!

	Obtained Characteristics 2010										
	PSB extraction				**PS extraction**			**SPS extraction**			
	/ ring [x10^11]	**ε_h and ε_v [mm · mrad] 1σ, norm.**	**nb batches**	**nb bunches**	**Ip / bunch [x10^11]**	**ε_h and ε_v [mm · mrad] 1σ, norm.**	**Nb bunches**	**Ip / bunch [x10^11]**	**ε_h and ε_v [mm · mrad] 1σ, norm.**	**ε_{longit} [eVs]**	**nb bunches**
[illegible]	16	2.5	2	4 + 2	1.3	2.5	72	1.15	3.6	≤ 0.8	1 - 4 x 72
LHC25 High int.	25	3.6/4.6	2	4 + 2	1.7 (1.9)	5	72	1.5	**~ 10**	~ 0.8	1 – 4 x 72
LHC50 (SB)	16	2.5	1	6	1.3	2.5	36	1.15	2.5	≤ 0.8	1 - 4 x 36
LHC50 High int. (SB)	24	3.5	1	6	1.8	3.5	36	**1.5**	**3.5**	≤ 0.8	1 - 4 x 36
LHC75 (SB)	11	1.5	1	6	1.3	1.8	24	1.2	2	≤ 0.8	1 - 4 x 24
LHC150	5	< 1.5	1	6	1.2	< 2	12	1.1	< 2.5 (1.6)	≤ 0.8	1 - 4 x 12

	Possible Characteristics 2011										
	PSB extraction				**PS extraction**			**SPS extraction**			
	Ip / ring [x10^11]	**ε_h and ε_v [mm · mrad] 1σ, norm.**	**nb batches**	**nb bunches**	**Ip / bunch [x10^11]**	**ε_h and ε_v [mm · mrad] 1σ, norm.**	**nb bunches**	**Ip / bunch [x10^11]**	**ε_h and ε_v [mm · mrad] 1σ, norm.**	**ε_{longit} [eVs]**	**nb bunches**
LHC25 (DB)	16	2.5	2	4 + 2	1.3	2.5	72	1.1 5	3.6	0.7	1 - 4 x 72
LHC50 (SB)	24	3.5	1	3 x 2	1.75	3.5	36	1.45	3.5	≤ 0.8	1 - 4 x 36
LHC50 (DB)	8	1.2	2	4 + 2	1.3	1.3	36	**1.15 (?)**	**1.5 (?)**	≤ 0.8	1 - 4 x 36
LHC75 (SB)	11	1.5	1	3 x 2	1.3	1.8	24	1.2	2	≤ 0.8	1 - 4 x 24
LHC75 (DB)	5.5	0.9	2	4 + 2	1.3	0.9	24	**1.2 (?)**	**1 (?)**	≤ 0.8	1 – 4 x 24
LHC150 (SB)	5	< 1.5	1	3x 2	1.2	< 2	12	1.1	< 2.5 (1.6)	≤ 0.8	1 - 4 x 12

The LHC50 and LHC75 double batch beams were not used in 2010.

- LHC50DB characteristics remain to be confirmed and can perhaps be pushed
- LHC75DB characteristics at extraction of SPS were never obtained, “tentative guess”

Plans for the Injectors Upgrade

- **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 numerous equipment (power supplies, magnets, RF…)**

⇒ **Procure spares**

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

Draft planning

- **2011 – 2013:** ***Linac4 construction & study, design and prototyping for PSB, PS, SPS (+ probably Linac3 and LEIR)***
  - **April 2011:**
    - **detailed work program for the period 2011-2013**
    - **baseline technical solutions**
  - **End 2011: detailed specifications from HL-LHC**
  - **April 2013: TDR**
- **2013 – 2015:** ***Construction***
- **2016 – 2017:** ***Installation and commissioning***

Plans for the Injectors Upgrade (3/17)

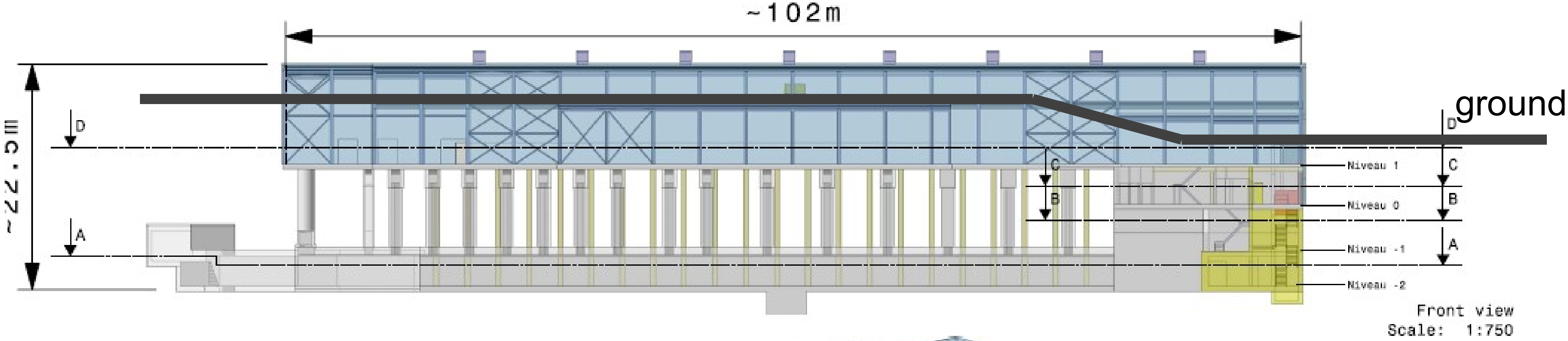
Progress with the Linac4 Project:

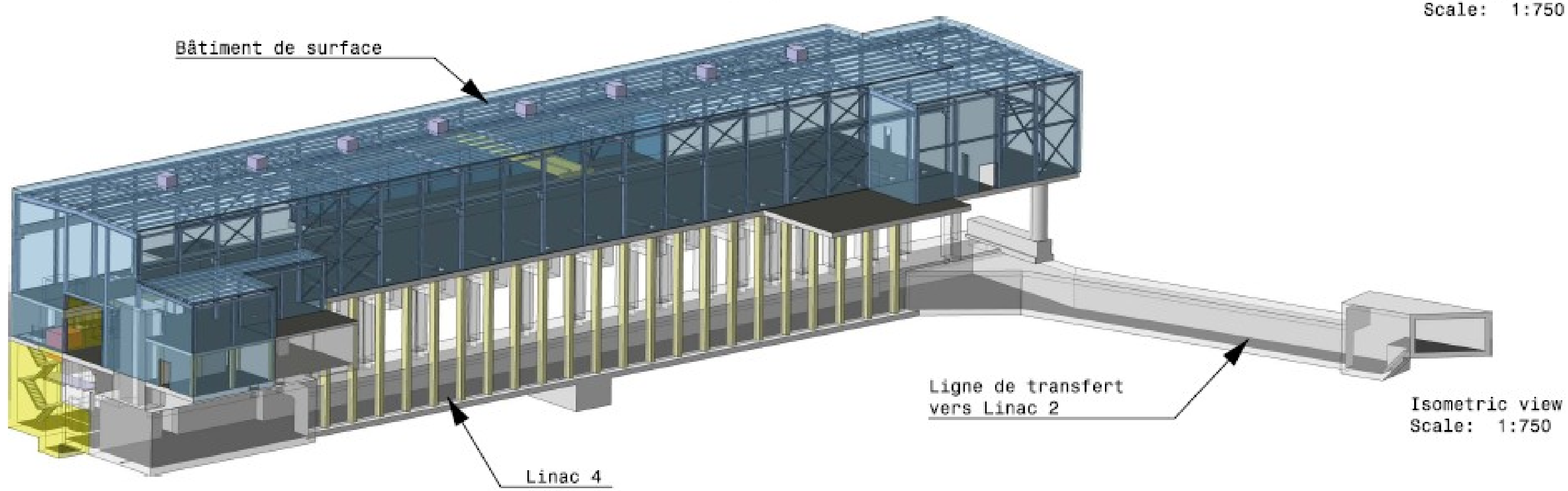
-1) Building completion in October 2010

Plans for the Injectors Upgrade

Progress with the Linac4 Project:

-1) Building completion in October 2010



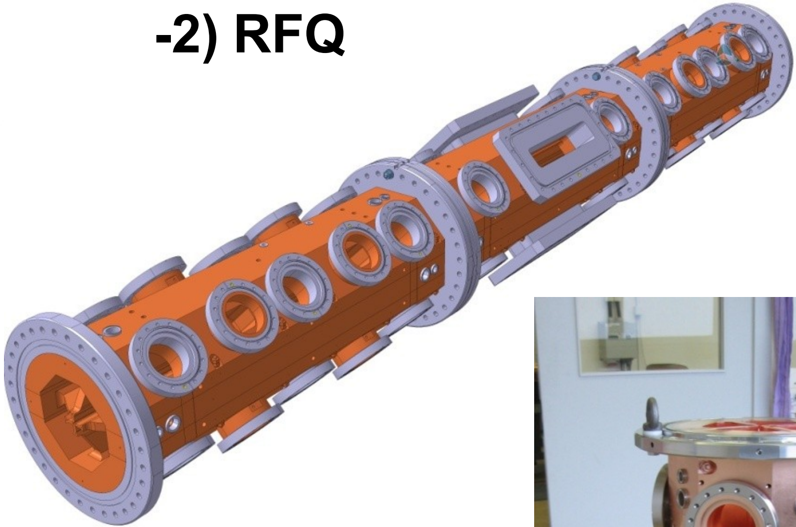


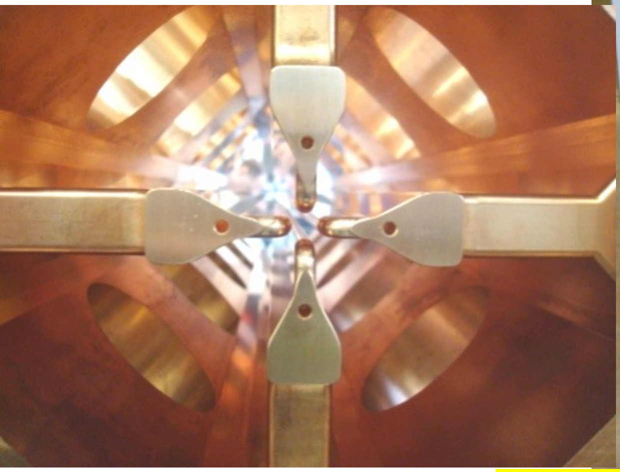
- Design of building started in December 2006.
- Overall floor surface of Linac4 installations = 3’305 m2 (over 4 levels)
- Completion in October 2010

Plans for the Injectors Upgrade

(5/17)

Progress with the Linac4 Project:
-2) 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.

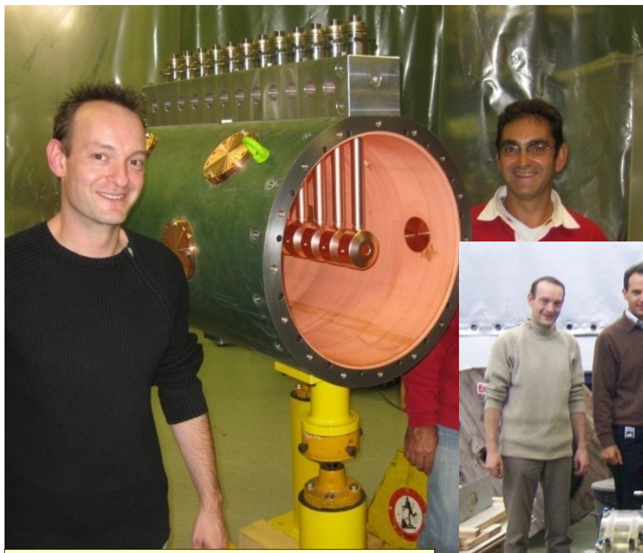
Progress with the Linac4 Project:
-3) Accelerating structures

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.

Increased PSB to PS transfer energy (1/2)

From K. Hanke

Outcome of the Task Force nominated 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

1082646-000

CERN Div./Group or Supplier/Contrac
BE-OP

EDMS Document No
1082646 v.3

The **PSB Upgrade** Working Group

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.

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Plans for the Injectors Upgrade

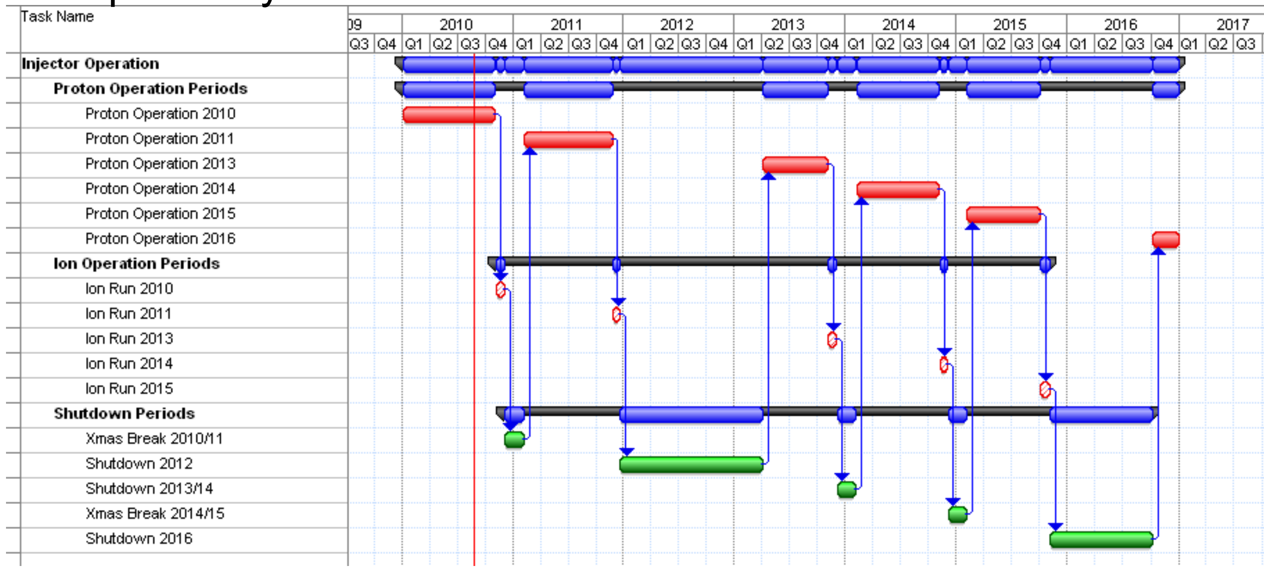
Increased PSB to PS transfer energy (2/2)

(8/17)

From K. Hanke

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

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



Plans for the Injectors Upgrade

PS performance potential with 2 GeV injection (1/2) (9/17)

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)

Plans for the Injectors Upgrade

PS performance potential with 2 GeV injection (1/2)

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

SPS performance potential (1/2)

From E. Shaposhnikova

Intensity limitations for 25 ns beam - 2010

intensity /bunch	Origin	Leads to	Present/future cures/measures
0.2×10^{11}	longitudinal multi bunch instability due to loss of Landau damping (longitudinal impedance)	- beam loss during ramp - bunch variation on FT	(FB, FF, long. damper) - 800 MHz RF system - emit. blow-up → RF - low γ_t optics
0.7×10^{11}	e-cloud due to the StSt vacuum chamber (δ_{SEY}=2.5, 1.3 is critical for SPS)	- dynamic pressure rise - transv. (V) emit. blow-up - instabilities - losses (via high chrom.)	- scrubbing run ($\delta \to 1.6$) - high chrom. (0.2/0.4) - transv. damper (H) - (50/75 ns spacing) - coating ($\delta \to 1.0$)
1.3×10^{11}	not known exactly e-cloud, impedance, space charge, beam loading	- flat bottom/capture beam loss (>5%)	- (lower chromaticity) - WP, RF gymnastics - collimation
1.5×10^{11}	beam loading in 200 MHz RF system	- voltage reduction on FT - phase modulation	- feedback & FF - RF cavities shortening
1.6×10^{11}	TMCI (transverse mode coupling instability) due to transverse impedance	- beam losses - emittance blow-up	- higher chromaticity - low γ_t optics - transverse high bw FB

SPS performance potential (2/2)

From E. Shaposhnikova

Conclusions - Q&A

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

- now one can hope to reach single-bunch performance with 50&75 ns beams (~3 μm emittances at ultimate intensity); probably 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.) one can hope to be at the space charge limit (~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 ?

Plans for the Injectors Upgrade

(13/17)

e-clouds in the SPS (1/2)

From J.M. Jimenez

Operating the SPS with:

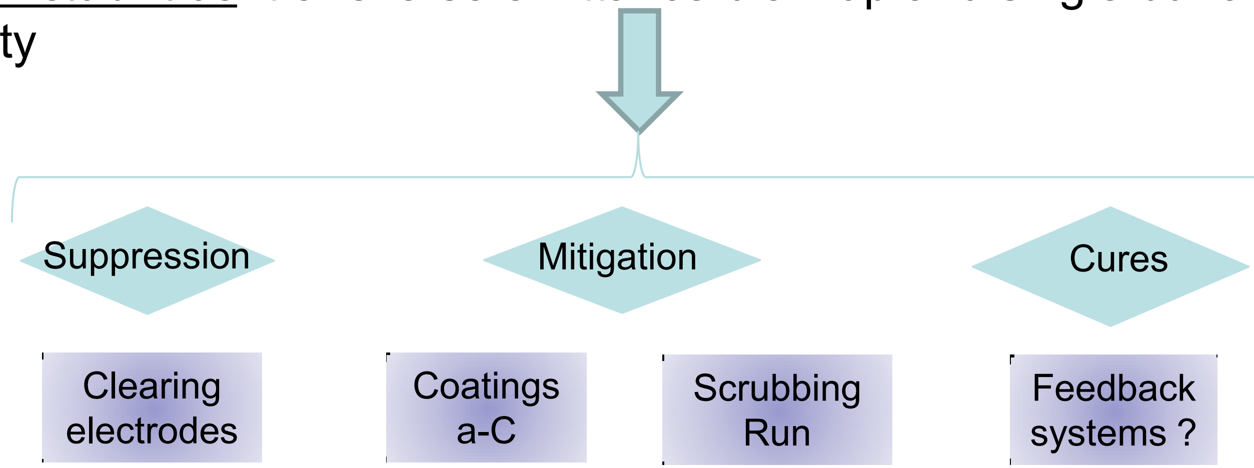
High bunch intensity, up to 2.5 10^{11} p/bunch

and/or

Small emittances (LHC requirements)

is impossible 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



Milestones for decision process and implementation are proposed:

- Strategy : October 2012 (for installation of pilot sector during LSD1)
- Full installation: LSD2

e-clouds in the SPS (2/2)

From J.M. Jimenez

Pending questions

Suppression: Clearing electrodes
- Aperture, impedance, technical solution, 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

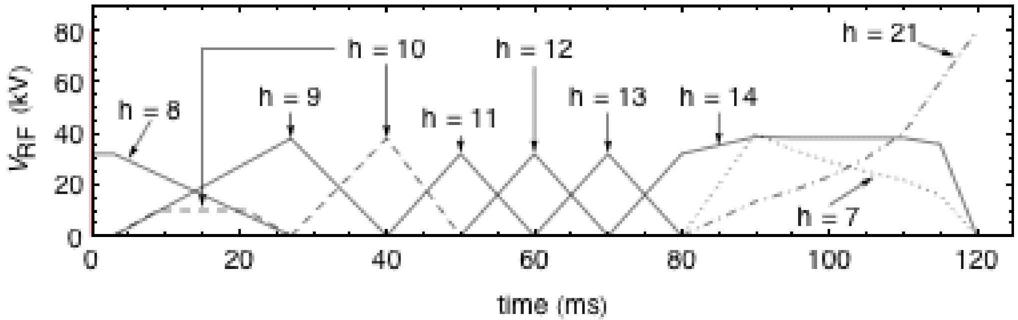
Simulations
- e-cloud budget, stability expected, emittance growth, impedance from electrodes, effectiveness of
- *If we rely on beam scrubbing in the LHC why not in the SPS?*

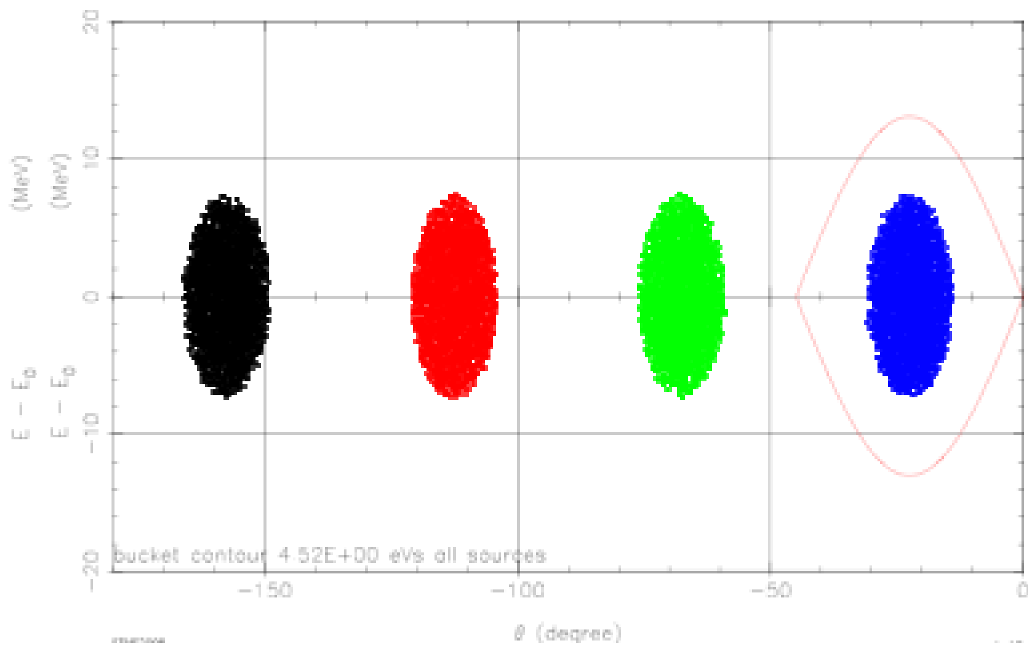
Alternative scenarios (1/2)

From C. Carli

Batch compression schemes using all PSB rings

- Scheme yielding 64 b
  - Brightness inc
  - Reasonable c
- Scheme yielding 48 b
  - Brightness inc situation: 2
  - Complex RF g compression s
- Any compression sch energy upgrade
- Tests can proceed im transfer from the I delivering beyond SPS before the en significant MD tim team).





Plans for the Injectors Upgrade

Alternative scenarios (2/2)

(…/17)

From C. Carli

Tentative parameters for a…

Energy range	[illegible]
Circumference	[illegible]
Repetition rate	[illegible]
RF volt…	[illegible]
[illegible]	[illegible]
[illegible]	…ion)
[illegible]	[illegible]
[illegible]	…27 eVs (determined by …most cases)
[illegible]	…15 cells and 3 periods, …ls in arc, straight with one cell
[illegible]	$4 < Q_{H,V} < 5$
…transition	~4
…gnet filling factor	56 %
M…m magnetic 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 solutions.

Conclusions

Beam specifications at LHC injection are essential to guide the choices in the injectors => need for close collaboration between HL-LHC and LIU projects.

New batch compression schemes in the PS can immediately help test the generation of beyond ultimate 25 ns bunch trains in the PS and, if successful, provide the possibility to explore the SPS potential.

Increasing the energy of the PSB is the primary solution for substantially upgrading the brightness that the PS can deliver.

A small size RCS replacing the PSB is an especially interesting alternative option.

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.

THANK YOU
FOR YOUR ATTENTION!

SPS performance potential

From E. Shaposhnikova

Main lessons/results from 2010

Nominal 25 ns beam in good shape: low beam losses (5%) even with low ξ_v = 0.1

Ultimate (injected) beam - needs studies

- 25 ns: large losses and emittances, instabilities
- 50 ns: 15% losses, 1.5x10^{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