Accelerator **P**hysics and synchrotron **D**esign

LHC injectors' upgrade plan

- Introduction: reminder
- News since LUMI06:
  - CERN Council's decision
  - Updated needs for SLHC
  - Updated list of future accelerators
- Generation of the beams for SLHC in the new injectors
- Final words

R. Garoby
2/10/2007

INTRODUCTION

Today's performance of the LHC injection chain

	Maximum energy	Number of pulses for the next machine	Repetition period for LHC	Intensity/bunch within required emittances (at ejection)	Limitations
Linac2	50 MeV	1	1.2 s		▪ Too low energy
PSB	1.4 GeV	2	1.2 s	~ ultimate beam	▪ Too low injection energy (space charge)
PS	25 GeV	3-4	3.6 s	$1.5\ 10^{11}$ p/b (~ 90 % of ultimate beam)	▪ Transition / Impedance ? ▪ Poor longitudinal match with SPS ▪ Reliability (age)
SPS	450 GeV	12	21.6 s	$1.15\ 10^{11}$ p/b (nominal beam)	▪ Too low injection energy ▪ e-cloud ▪ Impedance
LHC				???	▪ Too low injection energy (DA, Snap-back) ? ▪ e-cloud ?

Unexpected beam loss: > 10 %

Main line of action (as proposed in mid-2006)

Guidelines: economy / reliability / timing / flexibility

Stage		Main effect	Additional benefits
1	**Linac4** [160 MeV, H^-]	▪ PSB beam brightness x2 => ultimate beam in PS in a single pulse	▪ Easier operation, flexibility ▪ New accelerator ▪ Possibility of > ultimate beam from the PS
2	**New PS** [~50 GeV, PS2]	▪ Higher injection energy in the SPS => better SPS performance ▪ New accelerator + less demand on the PS => higher reliability	▪ Shorter injection flat porch in SPS and LHC ▪ Potential injector for a new (higher energy) SPS
2'	**New injector for PS2**	▪ Reach full potential of PS2 (brightness & intensity) ▪ No PS any more => higher reliability	▪ Easier operation (minimum RF gymnastics in PS2 + shorter injection flat porch in SPS and LHC) ▪ New accelerator ▪ Flexibility
3	**New SPS** [>500 GeV]	▪ Reach full potential of LHC ▪ New accelerator => higher reliability	▪ Easier operation ▪ Potential injector for a DLHC

PROGRESS SINCE LUMI06 (Valencia - Oct. 2006)

Outcome of June Council
(quote from R. Aymar – June 2007) [1/3]

New Activities for the period 2008-2011

- **Second Theme: As a high priority, the renovation of the entire old injector complex should be started in order to eliminate the concern about reliability of LHC operation** in the longer term and **the technical bottlenecks in the present injection line.**
  - The first is to build Linac 4, capable of 160 MeV instead of 50 MeV and with a better emittance.
  - The second, to be executed in parallel to the first, is to push forward the design of PS2 and SPL.

This high priority programme should be fully completed in 2011, and requires a total of 55 MCHF and 185 FTEs.

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June Council (quote from R. Aymar – June 2007) [2/3]

- The Third Theme implements two statements from the European Strategy :
  - *"advanced accelerator and detector R&D programme to prepare for an LHC upgrade in luminosity and to contribute to the study and development of a high intensity neutrino facility";*
  - *"enhance the CLIC development to qualify the technology before the end of 2010".*
    - Magnet R&D 22 MCHF and 80 FTEs.
    - R&D for detectors 13.5 MCHF + 33 FTEs.
    - Enhancement of CLIC qualifying programme with CTF3. 12 MCHF + 60 FTEs.

The total estimated resources required for the third Theme has been reduced to 48 MCHF and 173 FTEs.

- The Fourth Theme includes activities that are of high scientific interest, but which rely only partially on CERN contributions and will require an agreement with outside partners for an amount that is currently unknown. The most important components of this Theme include:
  - A facility to be (re)built at CERN, for testing superconducting cavities.
  - High Intensity and Energy ISOLDE project (HIE - ISOLDE).

The fourth Theme includes activities which cannot be decided upon without reaching agreement within collaborations that will have to be established. Estimates of contributions from CERN are given but are far from being certain (41 MCHF + ~ 145 FTEs)

The management proposes to earmark some funds from 2010 onwards on this fourth theme at the level of 10 MCHF per annum.

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June Council (quote from R. Aymar – June 2007) [3/3]

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**.

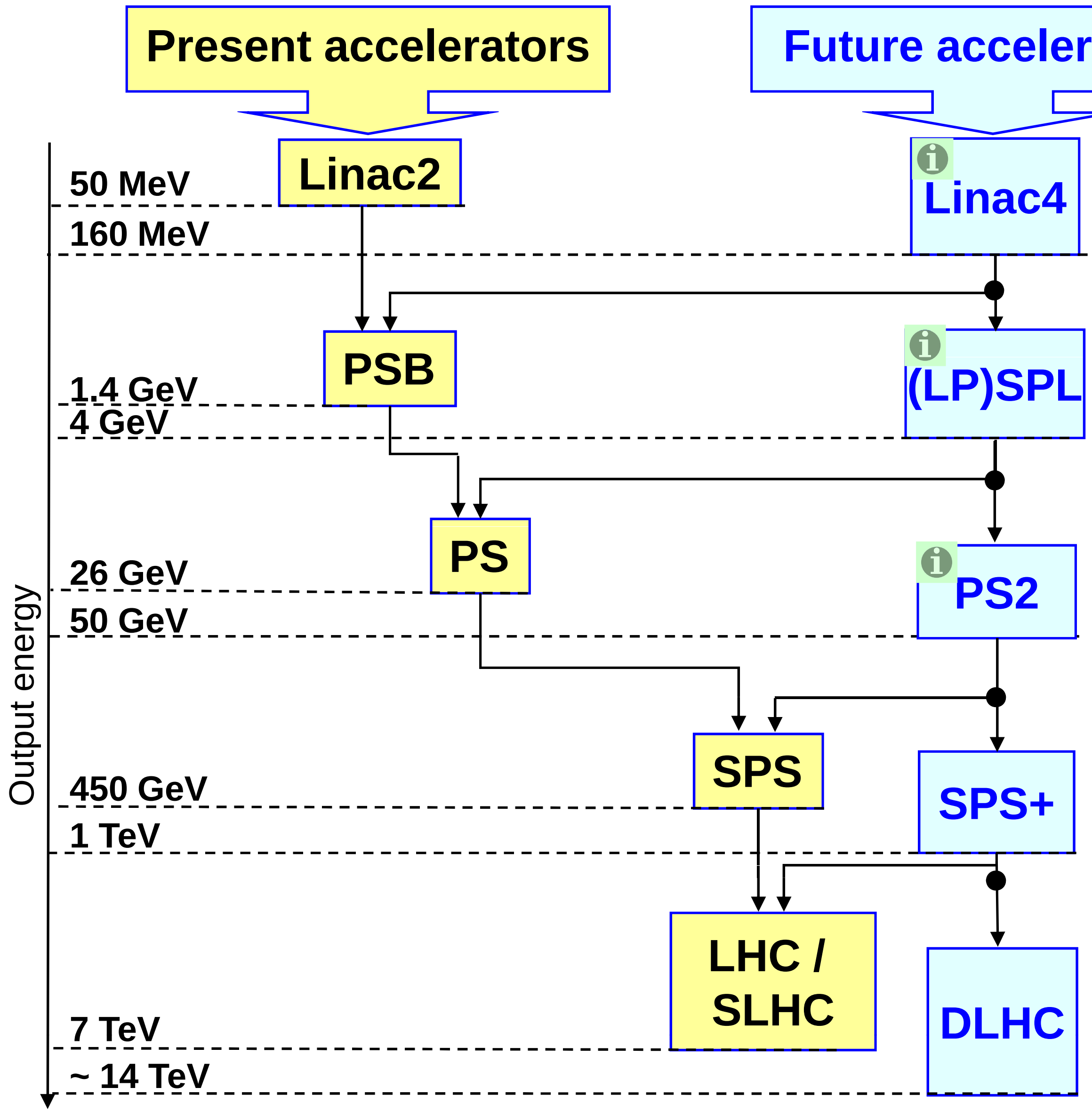
Updated needs of SLHC

Beam parameters [tentative…]	Bunch spacing [ns]	Protons per bunch* [10^{11}]	Transverse emittance in LHC [mm.mrad]	Intensity factor at PS injection*
Nominal	25	1.15 (1.4)	3.75	0.68 (0.81)
Ultimate	25	1.7 (2.1)	3.75	1 (1.2)
Ultimate & 12.5 ns spacing	12.5	1.7 (2.1)	3.75	2 (2.4)
2 x ultimate & 25 ns spacing	25	3.4 (4.1)	3.75 (blown-up to 7.5 in LHC)	2 (2.4)
3 x ultimate & 50 ns spacing	50	4.9 (5.9)	3.75	1.44 (1.73)
3.5 x ultimate & 75 ns spacing	75	6 (7.2)	3.75	1.17 (1.41)

Proposed maximum goal

* Case of 100 % (80 %) transmission PS → LHC

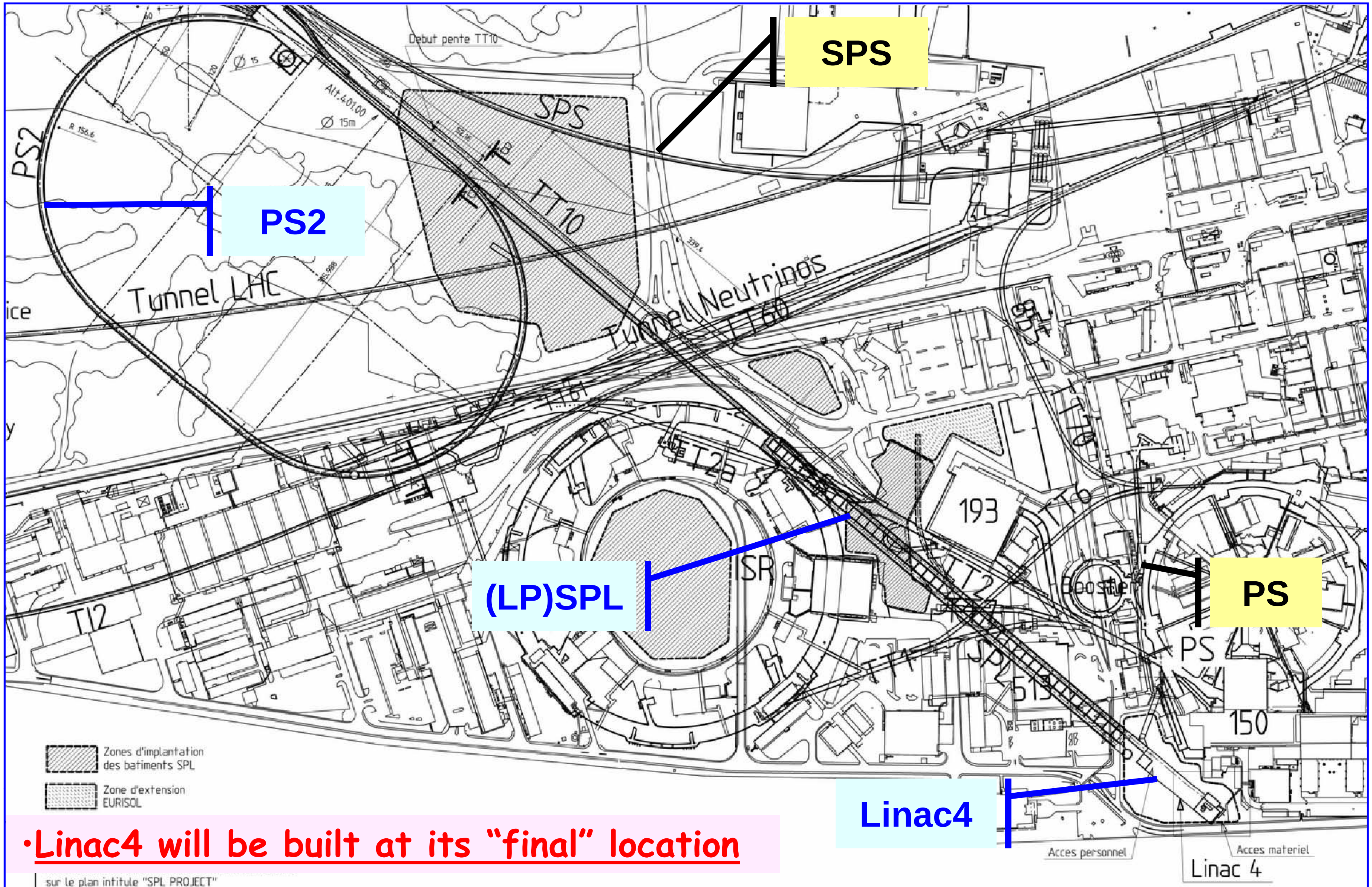
Updated list of future accelerators



- (LP)SPL is the baseline injector for PS2
- PS2 will use nc magnets
- PS2 size is 15/77 of SPS

(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

Layout of the new accelerators



•Linac4 will be built at its "final" location

Expected benefits of the successive stages of upgrade for the LHC

STAGE	1	2	3
DESCRIPTION (*new accelerator*)	*Linac4* PSB PS SPS	*Linac4* *(LP)SPL* *PS2* SPS	*Linac4* *(LP)SPL* *PS2* *SPS+*
Characteristics of beam entering PS/PS2	- Ultimate LHC beam in 1 PSB pulse instead of 2	- >2x ultimate LHC beam in 1 injection	- As in stage 3
Characteristics of beam entering SPS/SPS+	- 72 ultimate LHC bunches every 2.4s (instead of 3.6s) - Higher reliability (no long flat porch at PS injection) - Reduced injection flat porch (7.2s instead of 10.8s) - Possibility to study SPS limitation with brightness beyond ultimate	- Energy x2 (~50GeV) => improved SPS behaviour (farther from transition, reduced space-charge etc.) - Reduced injection flat porch (2.4s instead of 10.8s) - Highest reliability (no PS) - Capability to push the SPS to its maximum potential	- As in stage 3
Characteristics of beam entering LHC	- Capable of beam luminosity above nominal ($\geq 10^{34}$ cm^{-2}s^{-1}) - Higher reliability - Reduced filling time	- Beam characteristics for LHC luminosity upgrade (>> 2.5 10^{34} cm^{-2}s^{-1}) - Highest reliability - Minimum filling time	- As in stage 3 + - Energy x2 (~1 TeV) - Capability to push the LHC to its maximum potential - Adequate for DLHC

Expected benefits of the successive stages of upgrade for other CERN users

	STAGE		
	1	2	3
DESCRIPTION (*new accelerator*)	*Linac4* PSB PS SPS	*Linac4* *(LP)SPL* *PS2* SPS	*Linac4* *SPL* *PS2* SPS
β beam	-	-	++ (γ ~100)
ν Factory	-	-	+++ (~5 GeV prod. beam)
k, μ	-	~400 kW beam at 50 GeV	~400 kW beam at 50 GeV
EURISOL	-	-	+++

SCENARIOS FOR GENERATING THE BEAMS FOR SLHC IN THE INJECTOR COMPLEX

(in consultation with E. Shaposhnikova and M. Benedikt)

"Direct" capability of the upgraded injectors

Direct = without any specific gymnastics

By design (LP)SPL + PS2 will be able to provide 4×10^{11} p/bunch
at 50 GeV with any spacing multiple of 25 ns
=> **(provided that the SPS is improved accordingly)**

3.4×10^{11} p/bunch with n$\times$25 ns spacing circulating at 7 TeV in LHC

Conclusion:

- OK for 25 ns scenario with dipoles inside the detectors
- 70 % of the intensity required for the 50 ns scenario. To reach 100 %, the bunches can be generated
  - in PS2
  - in the SPS
  - ~~in the LHC~~

Generation in PS2 of the 50 ns bunch train for SLHC

Generation of 50 ns bunch train with 6×10^{11} p/b in PS2 necessitates:

- Enough voltage for bunch shaping before transfer to the SPS [$3\times V_{h=180}$(ultimate)]
- SPS capability to handle 6×10^{11} p/b (ε_L~0.7 eVs) through all the energy range

Ref.	Description	Requirements	Comments
PS2/1	▪ LPSPL chopping ▪ Capture & acceleration on h=90 ▪ Population of 25 ns satellites with additional h=180	▪ RF system in PS2 can operate at 20 MHz with full voltage	▪ **Simple** ▪ **Fast** ▪ **Cost of tunable RF system** ▪ **Needs implementation from the start** ▪ **Control of population of satellites**
PS2/2	▪ Capture & acceleration on h=180 in PS2 ▪ Merge bunches at high energy => capture on h=90 with slight asymmetry to create satellites	▪ Fixed freq. 20 MHz system in PS2 with limited voltage ▪ Long flat top at 50 GeV in PS2	▪ Medium complexity ▪ Longer cycles ▪ **Lower RF cost** ▪ **Can be implemented later** ▪ **Control of population of satellites**

Generation in SPS of the 50 ns bunch train for SLHC (1/2) - Merging scenarios

Generation of 50 ns bunch train with 5.4×10^{11} p/b in SPS necessitates:

- 2 PS2 bursts to provide ~ 340 bunches (3×10^{11} p/b) spaced by 25 ns [~ 4/11 of SPS]
- Voltage for bunch shaping in PS2 before transfer to the SPS [$1.5 \times V_{h=180}$(ultimate)]

Ref.	Description	Requirements	Comments
SPS/1	▪ Capture of batches with 200 MHz (h=4620) ▪ Adiabatic merge of bunches at injection energy => capture on h=462 ▪ Accelerate on h=4620	▪ Fixed freq. 20 and 40 MHz systems in the SPS with limited voltage ▪ SPS capability to handle 6×10^{11} p/b (ε_L~0.7 eVs) through all the energy range	▪ **Beam probably unstable during merging !** ▪ Medium complexity ▪ **Reasonably fast** ▪ **Modest RF cost** ▪ **Can be implemented later** ▪ **Control of population of satellites**
SPS/2	More exotic gymnastics for a non-adiabatic merge of bunches ???	To be studied	As above except: ▪ More favourable for beam stability during merging if the bunches don't have to be stretched... **Is it enough?** ▪ **Does it address the population of satellites ?**

Generation in SPS of the 50 ns bunch train for SLHC (2/2) – Slip stacking scenarios

Generation of 50 ns bunch train with 5.4×10^{11} p/b in SPS necessitates:

- 4 PS2 bursts to provide ~ 340 bunches (3×10^{11} p/b) spaced by 50 ns [~ 8/11 of SPS]
- Voltage for bunch shaping in PS2 before transfer to the SPS [$1.5 \times V_{h=180}$(ultimate)]

Ref.	Description	Requirements	Comments
SPS/3	■ Capture batches with 200 MHz (h=4620) ■ Slip stacking at injection energy => capture on h=4620 ■ Accelerate with 200 MHz (h=4620)	■ SPS capability to handle 6×10^{11} p/b (ε_L>1 eVs) through all the energy range	■ **Emittance after gymnastics ?** ■ **Recapture loss?** ■ **How to populate satellites ?** ■ Medium complexity ■ Slow ■ **~No RF cost** ■ **Can be implemented later**
SPS/4	As above but at higher energy	■ SPS capability to handle 6×10^{11} p/b (ε_L>1 eVs) through part of the energy range (or only at 450 GeV if done there)	■ **Emittance after gymnastics ?** ■ **Recapture loss?** ■ **How to populate satellites ?** ■ Minimum peak current during most of cycle ■ Medium complexity ■ Slow ■ **~No RF cost** ■ **Can be implemented later**

Guidelines for future work

- Very preliminary
- Needs detailed calculation of parameters
- Needs detailed simulations
- Possibility of new ideas

Importance of SPS improvement studies ! (E. Shaposhnikova)

	If SPS can accelerate 6×10^{11} p/b (ε_L~0.7 eVs)	If SPS <u>cannot</u> accelerate 6×10^{11} p/b (ε_L~0.7 eVs)
"Best" choice	**Generate beam in PS2 at capture [PS2/1]**	Slip stacking at high energy [SPS/4] ?
"Alternative" choice	Generate beam in PS2 by merging [PS2/2]	?
Other (new) ideas	?	?

FINAL WORDS

Summary

- The need to renovate the injectors is recognised. Projects and studies have been authorised and more resources are expected during the period 2008-2011.
- There has been significant progress during the past 12 months in the refinement of the solutions.
- The specifications of the new injectors comfortably cover the basic needs of all beams envisaged for SLHC, at least up to the exit of PS2. A lot of work is however required on the SPS to determine the actions to implement and the potential performance to expect.
- A procedure to generate the 50 ns bunch train for SLHC has to be worked out in the future with a deadline in 2010. The most promising scenario(s) will start being investigated soon.

Conclusion

- The pace of work is good and will accelerate in the near future.
- We have to strengthen our links with the community and establish new collaborations.

We need You !

REFERENCES

Stage 1: Linac4

Linac4 project team (M. Vretenar)

Linac4 beam characteristics

Ion species	H^-
Output energy	160 MeV
Bunch frequency	352.2 MHz
Max. repetition rate	2 Hz
Beam pulse duration	0.4 ms
Chopping factor (beam on)	62%
Source current	80 mA
RFQ output current	70 mA
Linac current	64 mA
Average current during beam pulse	40 mA
Beam power	5.1 kW
Particles p. pulse	$1.0\ 10^{14}$
Transverse emittance (source)	0.2 mm mrad
Transverse emittance (linac)	0.4 mm mrad

Stage 1: Linac4

- Direct benefits of the new linac
  - Stop of Linac2:
    - **End of recurrent problems with Linac2 (vacuum leaks, etc.)**
    - **End of use of obsolete RF triodes (hard to get + expensive)**
  - Higher performance:
    - **Space charge decreased by a factor of 2 in the PSB**

      => potential to double the beam brightness and fill the PS with the LHC beam in a single pulse,

      => easier handling of high intensity. Potential to double the intensity per pulse.
    - **Low loss injection process (Charge exchange instead of betatron stacking)**
    - **High flexibility for painting in the transverse and longitudinal planes (high speed chopper at 3 MeV in Linac4)**
  - First step towards the SPL:
    - **Linac4 will provide beam for commissioning LPSPL + PS2 without disturbing physics.**

- Benefits for users of the PSB
  - Good match between space charge limits at injection in the PSB and PS

    => for LHC, no more long flat bottom at PS injection + shorter flat bottom at SPS injection: easier/ more reliable operation / potential for ultimate beam from the PS
  - More intensity per pulse available for PSB beam users (ISOLDE) – up to 2×
  - More PSB cycles available for other uses than LHC

Stage 2: LPSPL + PS2

(LP)SPL study team
(R. Garoby)

LPSPL and SPL beam characteristics

Stage		2	2'
	CDR2	"LPSPL" for SPS & LHC	"SPL"
Energy (GeV)	3.5	4	5
Beam power (MW)	4	0.19	4 - 8
Rep. frequency (Hz)	50	2	50
Protons/pulse (x 10^{14})	1.4	1.2	1
Av. Pulse current (mA)	40	20	40
Pulse duration (ms)	0.57	1.9	0.4
Bunch frequency (MHz)	352.2	352.2	352.2
Physical length (m)	430	~460	535

3 different designs:

CDR2 (2006) based on 700 MHz high-gradient cavities

"LPSPL" for LHC (2007) with low beam power, for the needs of the LHC

"SPL" at higher energy, for the needs of neutrino production and/or EURISOL

Stage 2: LPSPL + PS2

PS2 study team (M. Benedikt)

PS2 beam characteristics

	PS2	PS
Injection energy kinetic (GeV)	4.0	1.4
Extraction energy kinetic (GeV)	~ 50	13/25
Circumference (m)	1346	628
Maximum intensity LHC (25ns) (p/b)	4.0×10^{11}	1.7×10^{11}
Maximum intensity for fixed target physics (p/p)	1.2×10^{14}	3.3×10^{14}
Maximum energy per beam pulse (kJ)	1000	70
Max ramp rate (T/s)	1.5	2.2
Repetition time at 50 GeV (s)	~ 2.5	1.2/2.4
Max. effective beam power (kW)	400	60

Stage 2: LPSPL + PS2 (3/4)

- Direct benefits of the LPSPL + PS2
  - Stop of PSB and PS:
    - **End of recurrent problems (damaged magnets in the PS, etc.)**
    - **End of maintenance of equipment with multiple layers of modifications**
    - **End of operation of old accelerators at their maximum capability**
    - **Safer operation at higher proton flux (adequate shielding and collimation)**
  - Higher performance:
    - **Capability to deliver 2.2× the ultimate beam for LHC to the SPS**
      => potential to prepare the SPS for supplying the beam required for the SLHC,
    - **Higher injection energy in the SPS + higher intensity and brightness**
      => easier handling of high intensity. Potential to increase the intensity per pulse.

- Benefits for users of the LPSPL and PS2
  - More than 50 % of the LPSPL pulses will be available (not needed by PS2)
    => New nuclear physics experiments – extension of ISOLDE (if no EURISOL)…
  - Upgraded characteristics of the PS2 beam wrt the PS (energy and flux)
  - Potential for a higher proton flux from the SPS