PLANS FOR THE UPGRADE OF THE LHC INJECTORS

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OUTLINE

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- Scenario 1: New injectors + SPS upgrade
- Scenario 2: Linac4 + consolidation & upgrade of existing injectors
- Status and planning

Introduction

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Motivation

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Introduction

1. Reliability ↑

The present accelerators are getting old (PS is 50 years old…) and they operate far beyond their initial design parameters

⇒ Need for replacement or consolidation & upgrade of the injectors

2. Performance ↑

- Luminosity depends directly upon beam brightness N/ε^*

$$L \propto \frac{1}{\beta^*} \frac{N_b}{\varepsilon_{X,Y}} \cdot N_b \cdot k_b$$

N_b : number of protons/bunch

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

k_b : number of bunches per ring

- Brightness is limited by space charge at low energy in the injectors

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

N_b : number of protons/bunch

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

R : mean radius of the accelerator

$\beta\gamma$: classical relativistic parameters

⇒ Need to increase the injection energy in the synchrotrons

Scenario 1:
New LHC injectors

Design goals

- For LHC operation
  - Higher beam brightness within nominal transverse emittances
  - Flexibility for generating various bunch spacings and bunch patterns
  - Reduction of SPS injection plateau and LHC filling time
- General design goals
  - High reliability and availability
  - Simplification of operation schemes for complete complex
  - Low beam losses in operation for complete complex
  - Potential for future upgrades of the accelerator complex

Specifications

- **Brightness (N/ε_n) for LHC beams**
  - Design goal: Twice higher brightness than “ultimate” 25ns beam with 20% intensity reserve for transfer losses

    $\Rightarrow$ **4.0×10^{11}ppb = $2 \times 1.7\times10^{11} \times 1.2$ in transverse emittances of 3µm**

- **Injection energy into the lowest energy synchrotron (PS2)**
  - Determined by the beam brightness of the LHC beam
  - Limit of incoherent space charge tune spread at injection to below 0.2

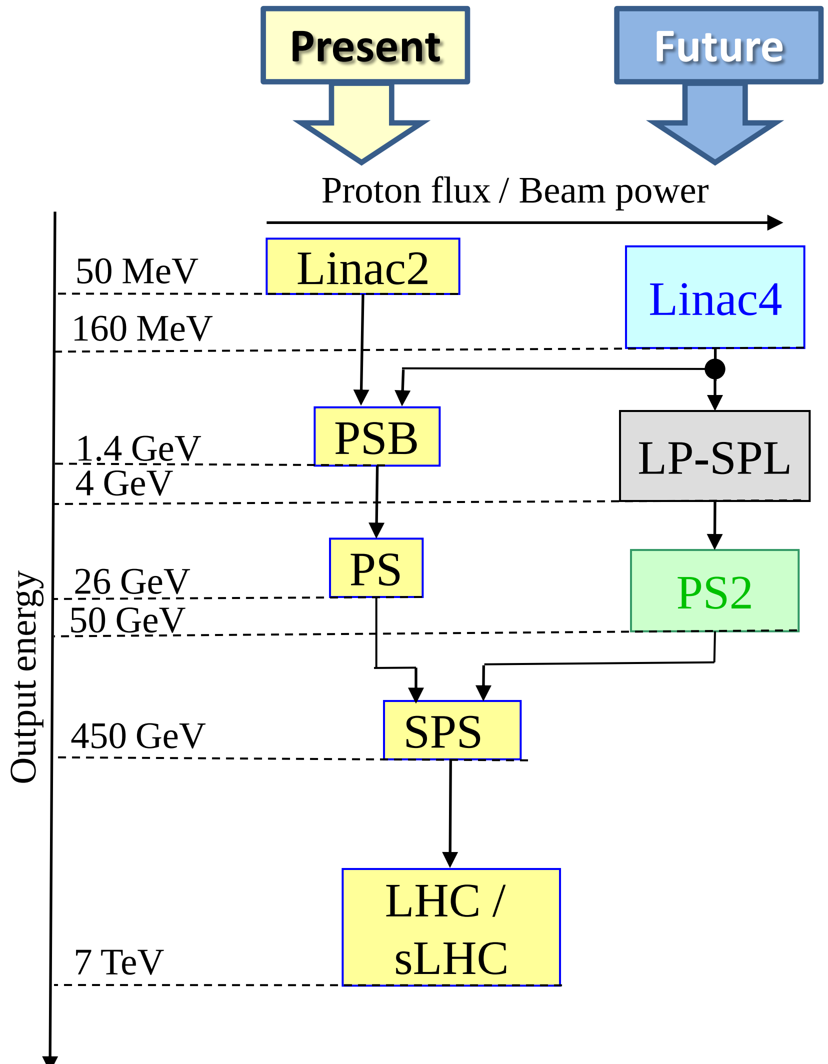
    $\Rightarrow$ **4 GeV injection energy**

- **Extraction energy**
  - Injection into SPS well above transition energy to reduce space charge effects and TMCI
  - Higher energy gives smaller transverse emittances and beam sizes and therefore reduced injection losses
  - Potential for long-term SPS replacement with higher energy

    $\Rightarrow$ **~50 GeV extraction energy**

Description

Scenario 1: New injectors + SPS upgrade



LP-SPL:
Low Power-Superconducting Proton Linac (4 GeV)

PS2:
High Energy PS (~ 5 to 50 GeV – 0.3 Hz)

sLHC:
"Super-luminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)

Site Layout

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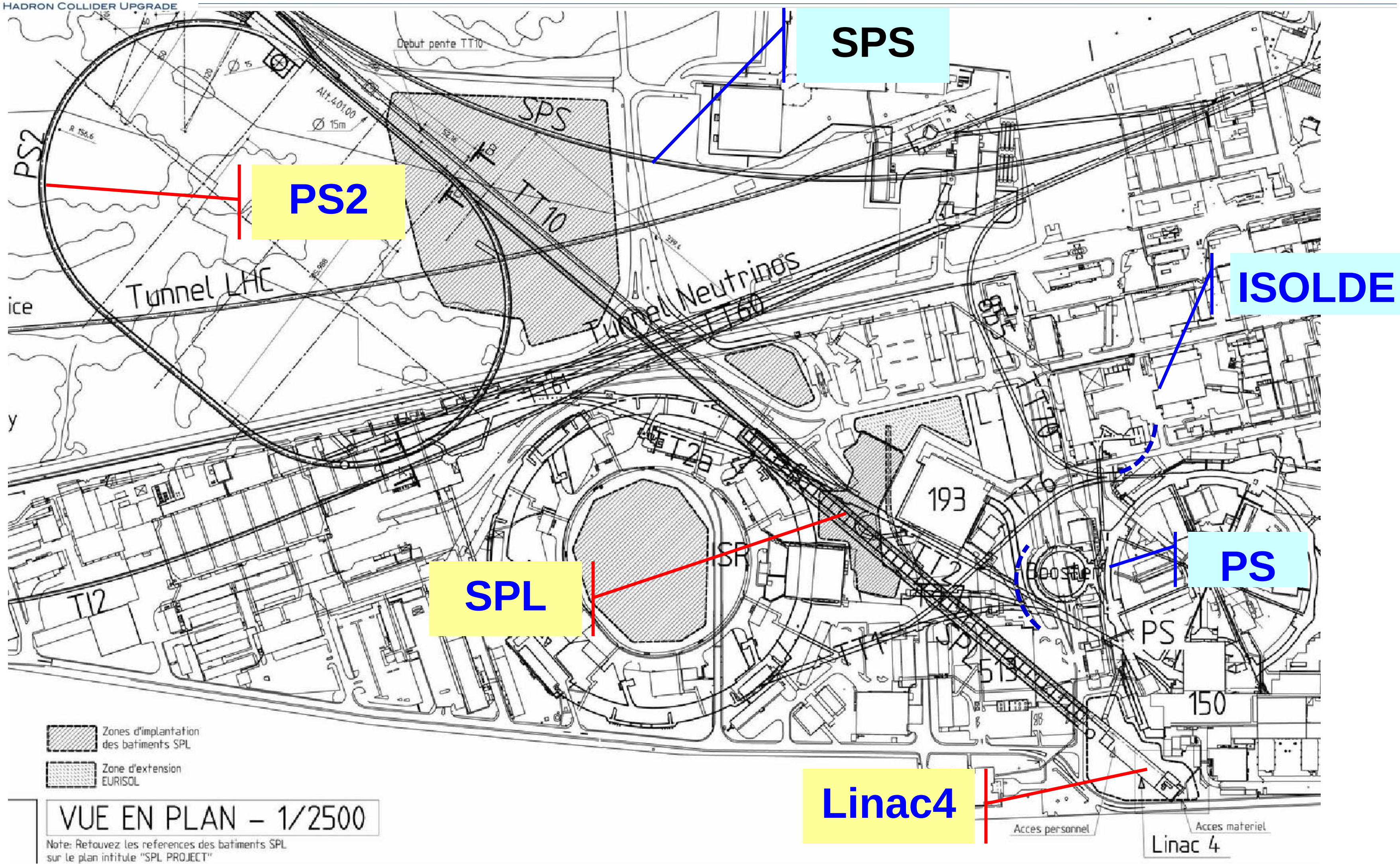
Scenario 1: New injectors + SPS upgrade



Linac4

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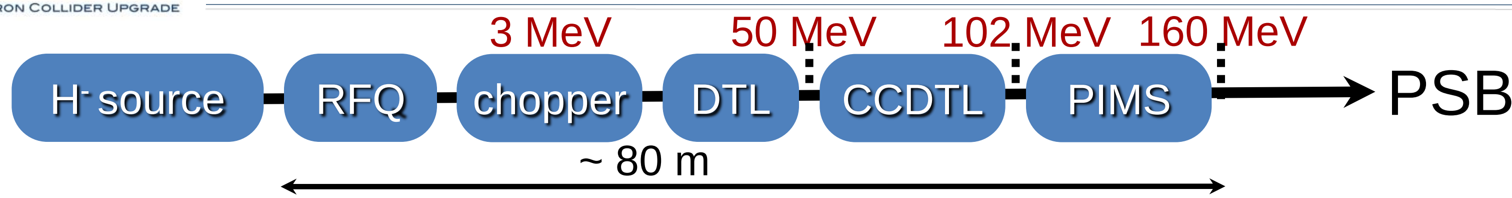

Scenario 1: New injectors + SPS upgrade

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**	**$\times 10^{14}$**
Transverse emittance	**0.4**	**π mm mrad**

Max. rep. rate for accelerating structures: 50 Hz

H^- charge exchange injection in the PSB

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

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

- **Structures and klystrons compatible with high power SPL**
- **Power supplies and electronics dimensioned for PSB and LP-SPL**

Scenario 1: New injectors + SPS upgrade

Low Power SPL

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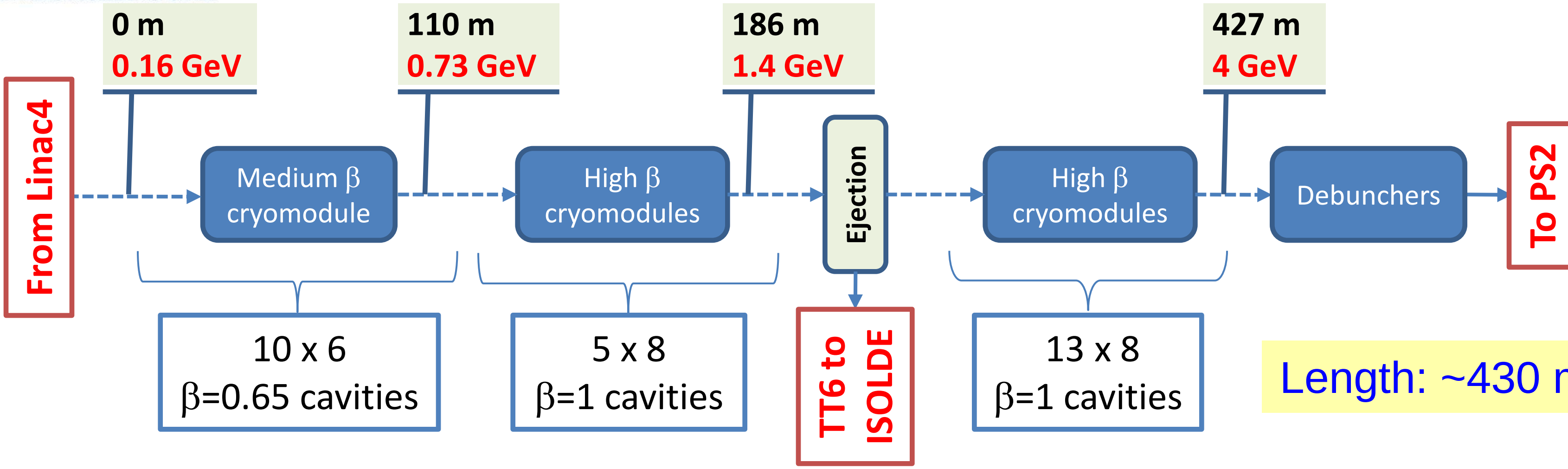

Length: ~430 m

Ion species	**H^-**
Output Energy	**4 GeV**
Bunch Frequency	**352.2 MHz**
Max. Rep. Rate	**2 Hz**
Max. Beam Pulse Length	**0.9 ms**
Linac pulse current	**20 mA**
Number of ions per pulse	**1.1×10^{14}**
RF frequency	**704.4 MHz**
Cooling temperature	**2 K**

Max. rep. rate for acc. structures & klystrons: 50 Hz

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PS2

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Scenario 1: New injectors + SPS upgrade

- **Lattice with imaginary γ_{tr}**
  - No transition crossing
    - No beam losses at transition
    - Simplification for operation by avoiding transition jump scheme
  - More complicated lattice design and more magnet types/families than in e.g. regular FODO lattices

- **Lattice structure**
  - Injection/extraction requirements limit tuning flexibility of long straight sections
  - Arcs have to provide not only imaginary gamma transition but also tuning flexibility
    - Regular arc modules
    - Dispersion suppressor modules to match to straight sections
    - Long straight sections with zero-dispersion

- **Longitudinal beam dynamics and RF**
  - No gymnastics (beam time structure established at injection)
  - Tunable RF system (~20 to 40 MHz)

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PS2 parameters

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Scenario 1: New injectors + SPS upgrade

Reason	Physical parameter	Value
Space charge PS2	Injection energy (kinetic)	**4 GeV**
SPS improvement	Ejection energy (kinetic)	**50 GeV**
LHC	Transverse normalized 1 sigma emittances at ejection for LHC	**3 π mm.mrad**
LHC	Longitudinal emittance/bunch with 25 ns bunch spacing at ejection	**0.35 eVs**
2.2 × ultimate brightness for LHC (includes 10% loss)	Nb of protons / bunch with 25 ns bunch spacing at ejection for LHC (total 168 bunches)	**4×10^{11} (6.7×10^{13})**
Flux for SPS / PS2 fixed target physics	Nb of protons / bunch with 25 ns bunch spacing (total)	**6×10^{11} ($\sim1\times10^{14}$)**
Possible bunch spacings in LHC (25, 50 & 75 ns)	Size (ratio PS2/SPS)	**15/77**
	Circumference	**1346.4 m**
	h_{RF} for 25 ns (resp. 50 or 75 ns) bunch spacing	**180 (resp. 90 or 60)**
Flux for SPS / PS2 fixed target + LHC filling time	Cycling period to 50 GeV (case of no injection flat porch)	**2.4 s**

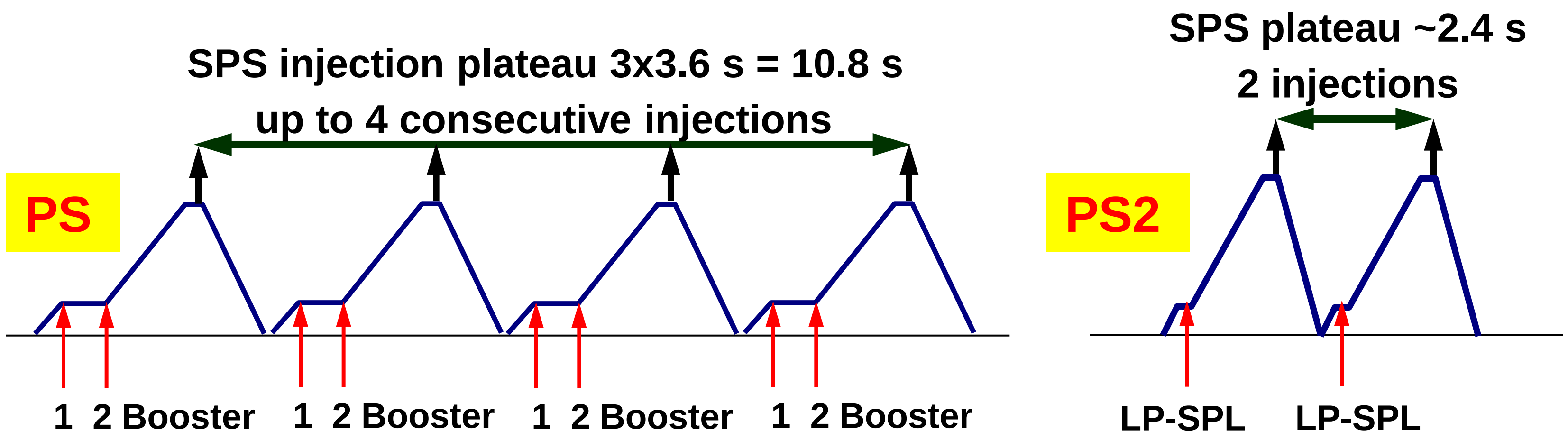
LHC beams from PS2 (i)

- **Nominal bunch train at PS2 extraction**
  - h=180 (40 MHz) with bunch shortening to fit SPS 200 MHz.
  - 168 buckets filled leaving a kicker gap of ~ 300 ns (50 GeV!)
    - Achieved by direct painting into PS2 40 MHz buckets using SPL chopping.
    - No sophisticated RF gymnastics required.
- **Beam parameters**
  - Extraction energy: 50 GeV
  - Maximum bunch intensity: 4E11 / protons per LHC bunch (25 ns)
  - Bunch length rms: 1 ns (identical to PS)
  - Transverse emittances norm. rms: 3 μm (identical to PS)
- **Any other bunch train pattern down to 25 ns spacing**
  - Straightforward with SPL 40 MHz chopping and 40 MHz system
    - No need for sophisticated RF gymnastics
    - Same brightness per bunch

LHC beam from PS2 (ii)

Scenario 1: New injectors + SPS upgrade

- **Example 25 ns beam from LP-SPL – PS2:**
  - PS2 will provide "twice ultimate" LHC bunches with 25 ns spacing
  - Bunch train for SPS twice as long as from PS
  - Only 2 injections (instead of 4) from PS to fill SPS for LHC
  - PS2 cycle length 2.4 s instead of 3.6 s for PS
    - Reduces SPS LHC cycle length by **8.4 of 21.6 s** (3x3.6 – 1x2.4)
- **Reduced LHC filling time**



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Preliminary planning

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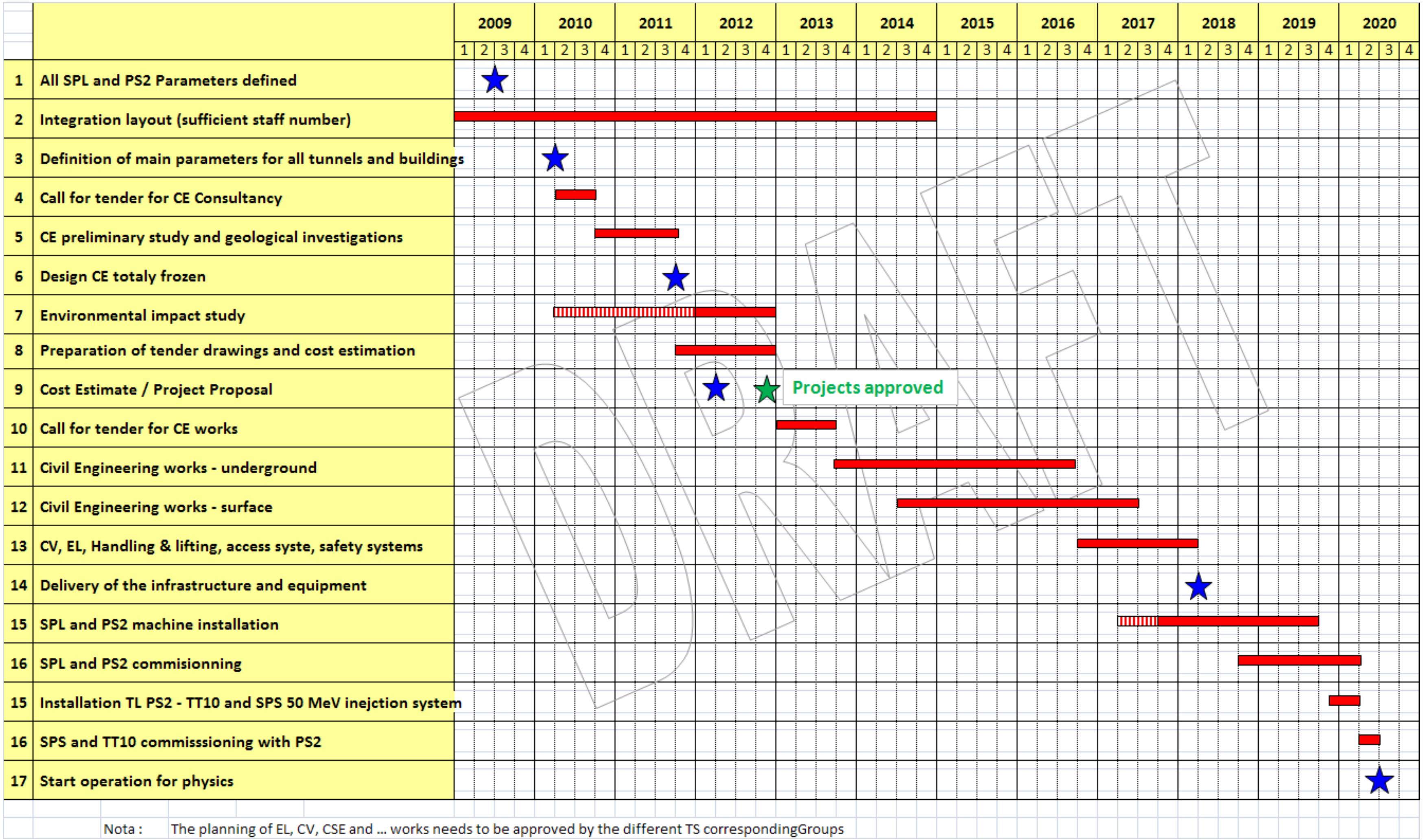
Scenario 1: New injectors + SPS upgrade



SPS upgrade needs

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Scenario 1: New injectors + SPS upgrade

SPS achievement wrt LHC needs

Parameters	SPS record at 450 GeV/c		LHC request 25 ns	
	25 ns	FT	nominal	ultimate
bunch intensity/10^{11}	**1.2**	0.13	1.2	**1.8**
number of bunches in SPS	288	4200	288	288
total intensity/10^{13}	3.5	**5.3**	3.5	5.2
long. emittance [eVs]	0.7	0.8	<1.0	<1.0
norm. H/V emitt. [µm]	**3.6**	8/5	**3.5**	3.5

⇒ Upgrade required for the ultimate LHC beam characteristics
[1.7x10^{11}/bunch, 25 ns spacing, 288 bunches]

⇒ Further upgrade necessary to match PS2 max beam characteristics
[4x10^{11}/bunch, 25 ns spacing, 336 bunches, total 1.3x10^{14}]

Known SPS limitations

- **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)

SPS summary

- **Main SPS limitations for ultimate intensity have been identified**. Measures to overcome them are under study (limited by resources)
- **The presence of other limitations is suspected. Beam studies with higher than nominal intensity are** needed to search for them.
- **e-cloud is a well-identified source of trouble. Means of mitigation are under study.** a-C coating of vacuum chamber is the best candidate for implementation
- **Upgrading the SPS RF system upgrade is mandatory** for ultimate intensities.
- 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.

Scenario 2: Linac4 + consolidation & upgrade of existing injectors

Recent data

- **LHC:**
  - Delayed start-up
  - Slower progress of performance than initially foreseen
  - Need for more work & resources to reach nominal performance
  - More worries on capability to operate beyond ultimate beam characteristics
- **New injectors:**
  - Realistic planning: availability in 2020-2022

    ⇒ need to invest for consolidating the existing accelerators
  - Uncertain SPS potential

⇒ Interest for investigating the possibility to upgrade PSB and PS

Main assumptions

- Linac4 is available.
- Maximum number of protons/PSB ring with Linac4 (limited by space charge effect at PSB injection): 3.6×10^{12}
- **Objective: maximize the bunch intensity of the LHC beam with 25 ns spacing.**
- Criterion:
  - Control the space charge tune shift $\Delta Q \propto -\frac{N_b}{\beta \gamma^2 \varepsilon_n}$
  - Reference parameters
    - $\varepsilon_n = 2.5\ \mu m$
    - Bunch length = 180 ns

    Nominal parameters used for the PSB upgrade from 1 GeV to 1.4 GeV
  - Constraint $|\Delta Q| \leq 0.3$

Space charge tune shift in the PS

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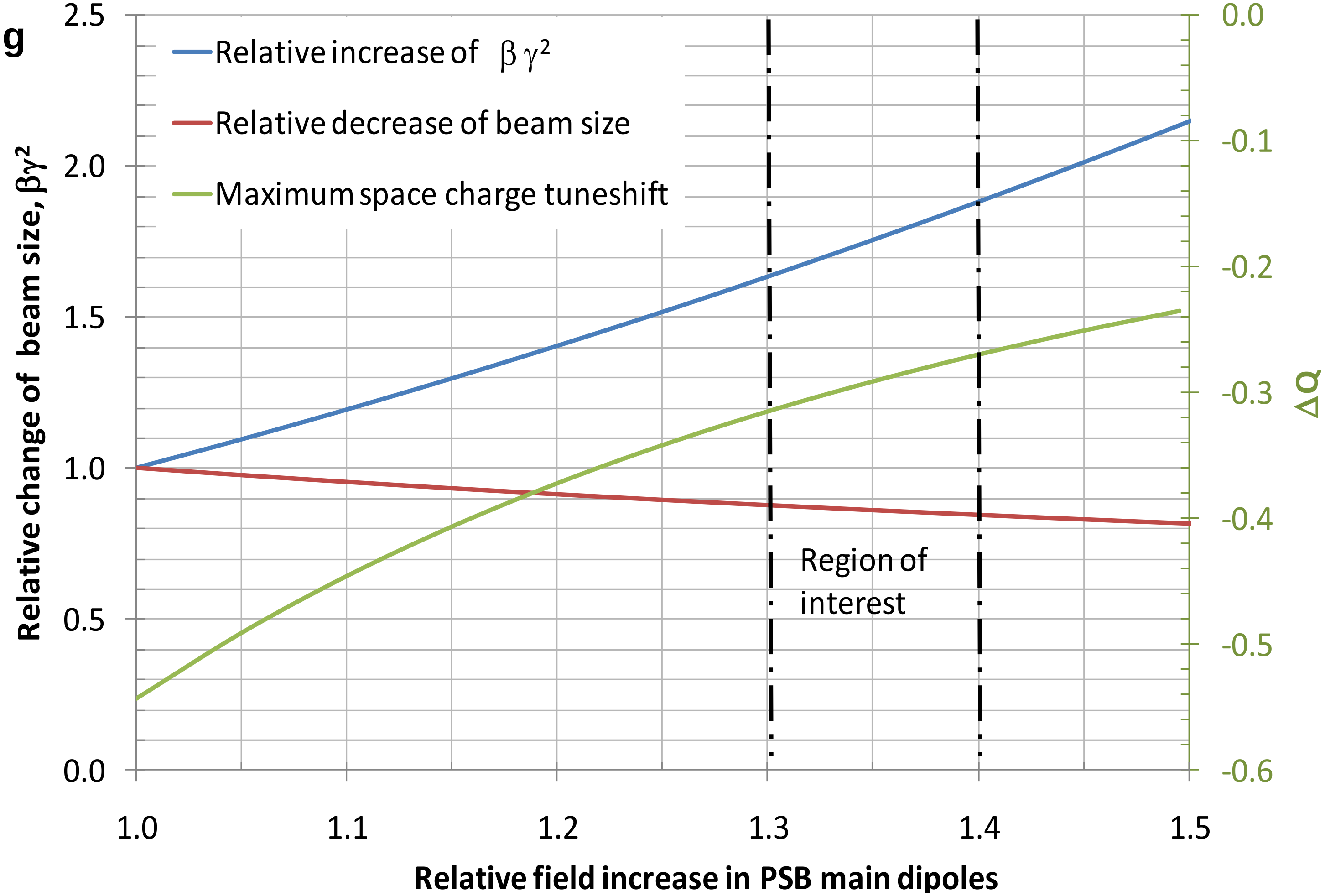
Scenario 2: Linac4 + upgrade & consolidation

Injected beam
3.6×10^{12} p/ring
$\varepsilon_n = 2.5\ \mu m$
$l_b = 180$ ns



Potential performance

- **Ultimate 25 ns LHC beam:**
  - 2.4E12 protons/bunch within 2.5 π mm mrad *
  - 6 bunches in two injections into the PS
  - translates into 1.7×10^{11} protons/bunch in the LHC ("ultimate"); includes 15% losses

  Out of range today: possible with Linac4.

- **Beyond Ultimate**
  - Theoretical upper limit of 3.24×10^{12} protons/bunch injected into PS (cf. M.Giovannozzi)
  - would translate into 2.7×10^{11} protons/bunch in the LHC; extremely optimistic (no losses).

  Need Linac4 and PSB energy upgrade.

* 3.5 π mm mrad at SPS extraction, includes budget for emittance blow up (not used)

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Beam dynamics (beyond space-charge)

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Scenario 2: Linac4 + upgrade & consolidation

- **Subjects:**
  - PSB at 2 GeV: nothing critical
  - PS: need to investigate:
    - longitudinal coupled-bunch instabilities during ramp and at flat top
    - electron cloud and transverse instabilities at flat top
    - resistive wall head-tail instabilities at flat bottom
    - TMCI at transition crossing
- **Actions:**
  - Need for machine studies (already started)
  - Cures/mitigation measures: suggestions exist for all subjects

Overview (PSB and PS)

Preliminary analysis

			Feasibility	Impact
1.	Beam Dynamics	BE/ABP	YES	
2.	Magnets, Magnetic Measurements	TE/MCS	YES	++
3.	RF System	BE/RF	YES	+
4.	Beam Intercepting Devices	EN/STI	YES	+
5.	Power Converters	TE/EPC	YES	+++
6.	Vacuum System	TE/VSC	YES	+
7.	Instrumentation	BE/BI	YES	
8.	Commissioning	BE/OP	YES	
9.	Extraction, Transfer, PS Injection	TE/ABT	YES	+++
10.	Controls	BE/CO	YES	
11.	Electrical Systems	EN/EL	YES	++
12.	Cooling and Ventilation	EN/CV	YES	++
13.	RP and Safety	DGS/RP	YES	
14.	Transport and Handling	EN/HE	YES	
15.	Survey	BE/ABP	YES	

Summary

Scenario 2: Linac4 + upgrade & consolidation

- **Showstopper identification completed**

→ **no showstoppers, but a number of significant modifications identified**

- **Costing and scheduling (work in progress):**

Implementing the energy upgrade before Linac4 (2015) is

a) schedule-/resource-wise **unrealistic**

b) **more costly** as consolidation will not be in place by then

- **Comparison of cases with Linac2 and with Linac4**

→ **firm recommendation to implement the energy upgrade with Linac4**

- **Interest of pulsing at 2 GeV only for LHC**

→ **no cost advantage: recommendation to operate at 2 GeV for all beams sent to the PS**

→ **minor saving possible in case ISOLDE 1 GeV option would be suppressed**

Status and planning

Linac4 Civil Engineering

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Status and planning

Accelerator tunnel

Equipment hall

Linac4 planning

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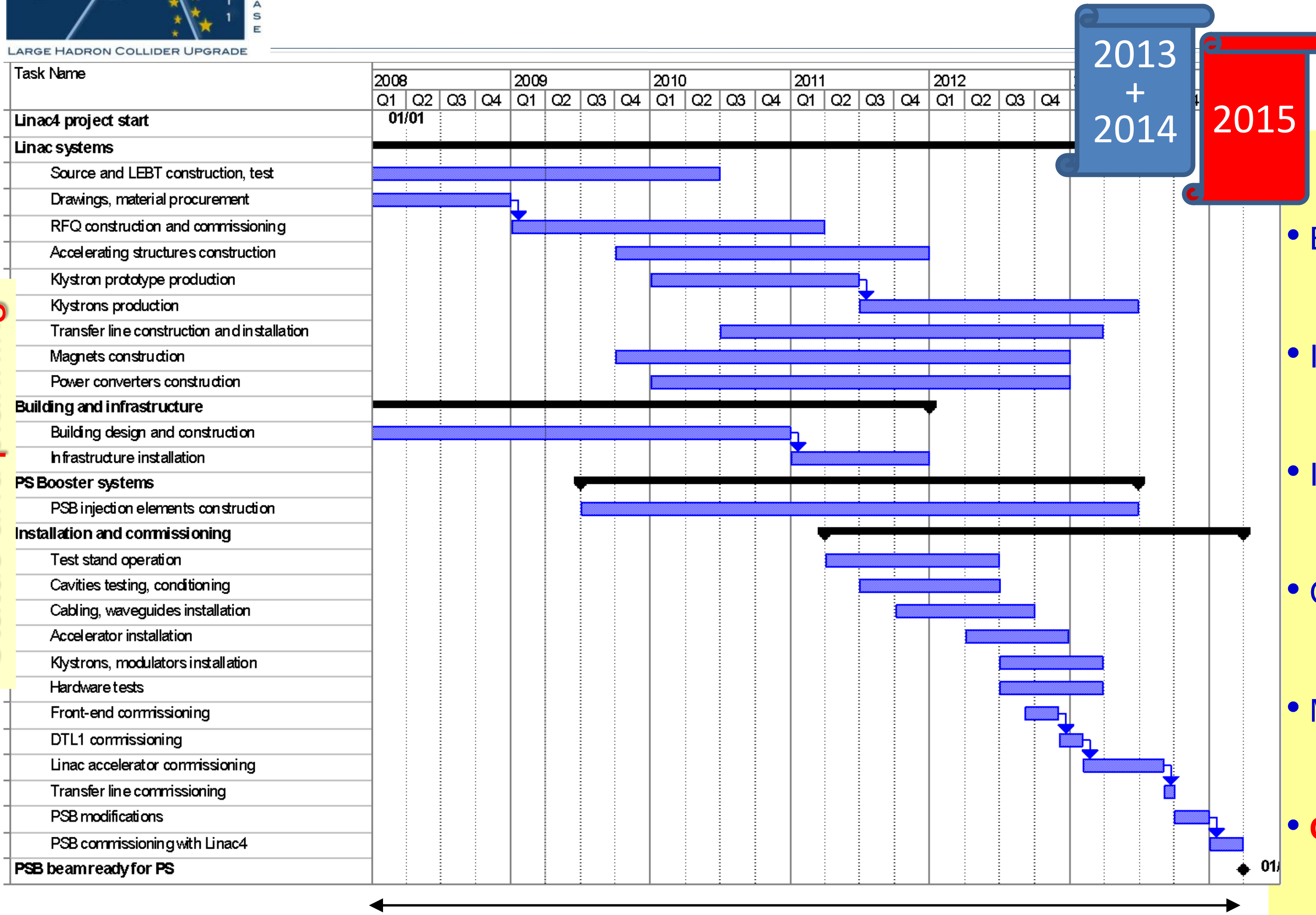
Status and planning



project duration: ~ 7 years

Milestones

- End CE works: December 2010
- Infrastructure: 2011
- Installation: 2011-2012
- Commissioning: 2012 till 2014
- Modifications PSB: shut-down 2014/15
- **Operation: Spring 2015**

Other accelerators

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Status and planning

- **Scenario 1 was the baseline until recently:**
  – A lot of work has been accomplished / collaborations established (see web-sites)

However, considering the present context (slide 21), and pending CERN Council decision on the MTP

- **Scenario 2 is favored:**
  – no construction of LP-SPL and PS2.
  – termination of studies to allow for the LP-SPL and PS2 to remain as possible fall-back solutions.
  – continuation of SPL R & D for high beam power in view of potential use in a neutrino facility.
  – **increase of the PSB to PS transfer energy.**
  – **consolidation and upgrade of PSB, PS and SPS.**

} **Completion in ~2015**

Reference slides

Complication in present operation:
e.g. 25 ns bunch train production in PS complex

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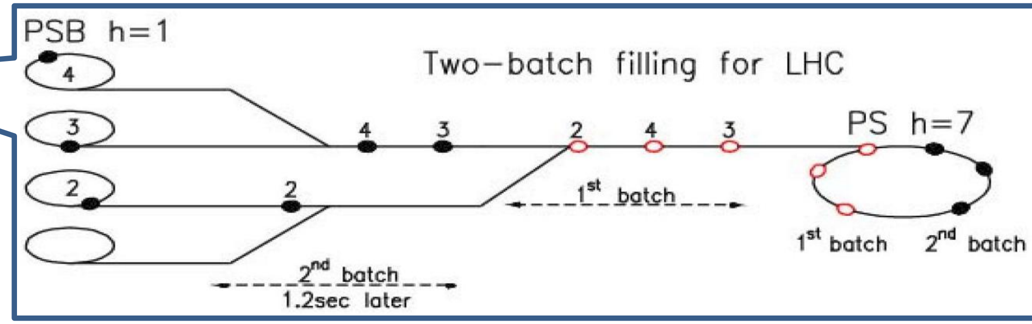
Scenario 1: New LHC injectors

1. Division by 2 of the intensity in the PSB (one bunch per ring and double batch filling of the PS)



2. Increase of the injection energy in the PS (from 1 to 1.4 GeV)
3. Quasi-adiabatically splitting of each bunch 12 times in the PS to generate a train of bunches spaced by 25 ns
4. Compression of bunches to ~4ns length for bunch to bucket transfer to the SPS
5. Stacking of 3-4 PS batches in the SPS and acceleration to 450 GeV