PS2 main parameters and basic choices

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- **Overview on basic design choices and PS2 parameters**
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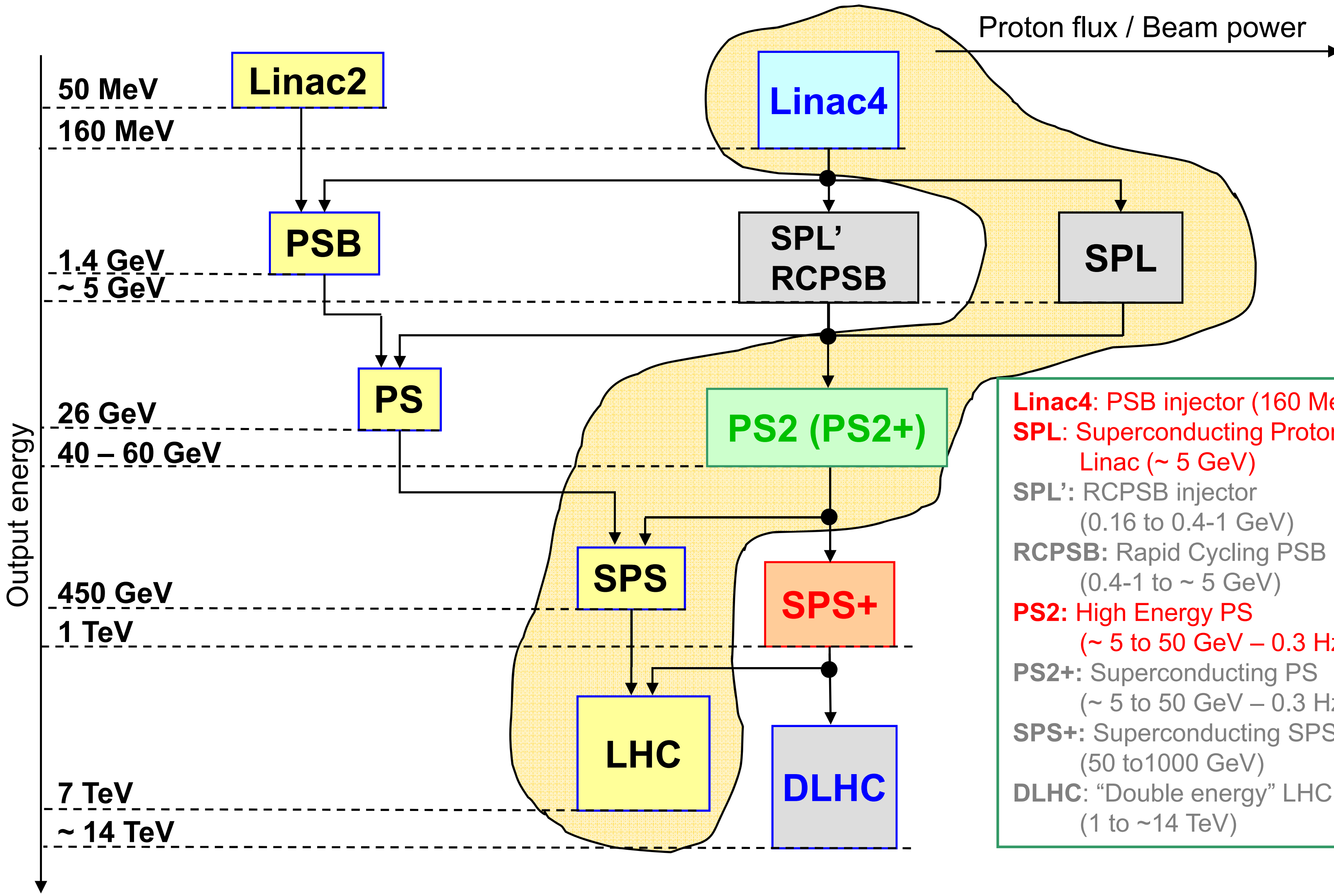
White Paper Studies for LHC Injector Upgrade



Linac4: PSB injector (160 MeV)
SPL: Superconducting Proton Linac (~ 5 GeV)
SPL': RCPSB injector (0.16 to 0.4-1 GeV)
RCPSB: Rapid Cycling PSB (0.4-1 to ~ 5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
PS2+: Superconducting PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
DLHC: "Double energy" LHC (1 to ~14 TeV)

Performance requirements

- **Beam brightness for LHC luminosity upgrade:**
  - **Reach twice brightness of the ultimate 25 ns LHC beam (~20% reserve for losses): 4.2×10^{11} per LHC bunch (inst. 1.7×10^{11})**
    - Determines average line density in the machine at injection and therefore the injection energy via incoherent SC tune spread.
- **Significantly higher injection energy into SPS (~50 GeV).**
  - **Injection into SPS well above transition energy**
  - **Reduced space charge at SPS injection**
  - **Smaller transverse emittances and reduced losses**
  - **Potential for long-term SPS replacement with higher energy.**
    - Ejection energy determines PS2 size and magnet requirements
- **As versatile as existing PS**
  - **Protons, ions, high intensity physics beams, slow extraction, etc.**

Considerations on machine size (i)

- Constraints from desired extraction energy ~50 GeV
  - Separated function (eventually complicated lattice for imag. γ_t)
  - Iron dominated dipoles B ≤ 1.8 T
  - Bending radius at 50 GeV ~100 m, bending length ~ 630 m
  - Additional space for quadrupoles: ~200 m (30% of dipoles)
  - Space requirements insertions: ~300m (RF, injection/extraction)
    - PS2 will have ~twice PS size i.e. R ~ 200 m and C ~ 1250 m.
- Constraints from filling SPS for physics
  - Complete filling of SPS circumference desired for HI FT physics
  - Use island multi-turn extraction scheme, similar to PS (5-turns)
    - Ideal PS2 length 1/5 SPS = 11/5 PS = 2.2 PS.

Considerations on machine size (ii)

- **Constraints from synchronisation (rf cogging)**
  - **$N \times h_{PS2} = K \times h_{SPS}$ is needed for correct synchronisation**
    - **Best candidates are (N, K) = (77, 15) or (77, 16)**
    - **Where 77/15 is preferred since 5 PS2 are slightly shorter than the SPS.**

- **Optimum length for PS2 from above arguments**
  - **PS2 = 15/77 SPS = 15/77 * 11 PS = 15/7 PS.**
  - **Circumference PS2 = 15/7 PS = 1346.4 m**
  - **Radius PS2 = 214.3 m**
  - **h (200MHz SPS) = 4620, h (40MHz SPS) = 924, h (40MHz PS2) = 180**

Considerations on magnet technology

- **Iron dominated magnets**
  - Coil either normalconducting or superconducting (SF option)
  - Same pole shapes and field quality for NC and SF variants
  - First NC design for dipoles and quadrupoles done.
  - SF R&D programme ongoing only for dipole
  - Short prototype for measurements end 2009/2010

- **Fast cycling high field SC option (co theta) ruled out**
  - Too high AC – losses therefore uneconomic!
  - Gain for machine energy increase limited and not required.

Considerations on injection energy

- **Incoherent space charge tune spread at injection:**
  - **Scaling from PS experience: with 1.4 GeV injection energy capable of producing the ultimate LHC beam (ΔQ_v ~-0.25)**

$$\Delta Q_{S.C.} \propto -\frac{N_b}{\varepsilon_n} \cdot \frac{1}{\beta\gamma^2} \cdot \frac{1}{B_b}$$

    - B_b… bunching factor (average / peak density for single bunch)
    - B_b will decrease by factor 2.15 when putting the same bunch in a machine with 2.15 larger circumference (**ΔQ prop. R**)!

- **PS2: 2.4 x ultimate brightness in a 2.15 larger machine**
  - **~5 times larger incoherent tune spread at given energy.**
  - **Compensation with ratio $\beta\gamma^2$ at injection:** $(\beta\gamma^2)_{PS2} \approx 5.1 \cdot (\beta\gamma^2)_{PS}$
    - **Injection energy PS2 ~ 4 GeV (ratio 4.9, for 4.2 GeV ratio 5.3)**
    - **Additional margin from bunching factor (PS: 150 ns / 327 ns)**

Integration in existing complex - Injection

- **With injector upgrade i.e. (LP) SPL replacing PSB + PS (LE)**
  - **H- injection at ~4 GeV**
- **Ion operation**
  - **Beam from LEIR at ~1.25 GeV p-equivalent, rigidity 6.67 Tm**
    - Requires LEIR upgrade: main converter, extraction elements, transfer line elements, rf system for LHC ion scheme with PS2.
- **With staged approach i.e. PS2 before/in parallel to LP(SPL)**
  - **Injection from <u>existing PS</u> (to bridge PSB to PS2 energy gap)**
    - PS running only at low energy, below transition (γ_t ~ 6.1).
    - Commissioning of PS2 in parallel to SPL and physics operation.
  - **Performance limited by**
    - PS SC limit at injection (line density corresponding to ultimate)
    - Filling pattern and cycling time (double batch PS -> PS2).

Integration in existing complex - Extraction

- **Several extractions towards the SPS:**
  - **Fast (single turn type)**
    - LHC beams
  - **"Continuous Transfer" multi-turn extraction (5-turn)**
    - Filling of SPS for fixed target physics.
  - **Both extractions also with ion beams?**

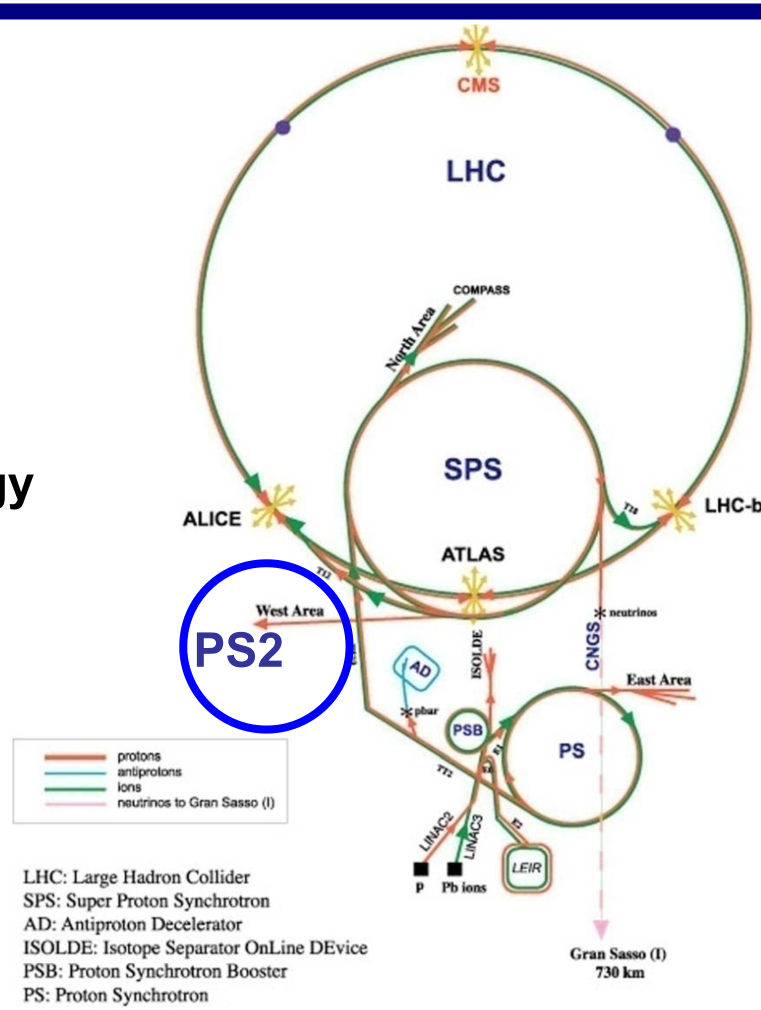
- **Extraction for physics at PS2**
  - **Slow resonant extraction**
    - High intensity fixed target (similar to SPS)
  - **Fast extraction**
    - Target test facility, etc.

PS2 experimental areas, anti-proton physics

- **Experimental area for PS2**
  - **For high power experiments an under ground or strongly shielded area will be mandatory**
    - PS EAST hall very limited for radiation protection reason
  - **For (low-intensity) test beams a facility on surface could be considered**
- **Anti-proton programme**
  - **No straightforward way to send p to AD**
    - ~ 1 km of transferline + reuse of PS tunnel for turning required
  - **Full PS2 potential for anti-proton production cannot be exploited with AD and AD target station**
    - Consider alternative solutions (new or modified/moved AD, etc.)
  - **Antiproton programme not defined in PS2 period (>2017)**
    - FAIR foresees antiproton programme from 2015.

Considerations on PS2 integration

- **PS2 has to link the PS complex (Linac4 + SPL) with the SPS.**
- **Tangent to TT2/TT10**
  - **Compatible with ions**
  - **Commissioning strategy**
  - **Possibility for (limited) p-operation from PS complex**
- **Best suited position**
  - **Final flat part of TT10**
  - **-50 m underground**
  - **Shielding OK**



Machine shape

- **Location of the machine at end of TT10**
  - Injection from SPL (parallel to TT10) (with short transfer line)
  - Injection of ions directly from TT10 for ions
  - Injection of protons directly from TT10 if required for commissioning or intermediate period.
  - Extraction towards the SPS via TT10 and existing SPS injection channel in point 1 with short transfer line
- **Optimisation leads towards a racetrack shape of the machine**
  - Two long zero-disperion straight sections, min. number of suppressors.
  - Super-symmetry 2 with mirror symmetry within superperiod, mirror planes centre arc and centre long straight section
  - One long straight section for injection and extraction
  - Other long straight section for RF

Linac 4
SPL
96,7
(460)
PROFIL EN LONG - H=1/2000 L=1/1000
Fourreau circulaire realise par carottage
Puis tubage 300x450mm
COUPE AMORCE SPL - 1/200e
PS2
TI2
Coupe A-A - 1/100e
TT10
Coupe B-B - 1/100e
Alt route 450.00
Alt 448.00
Pente 6.10%
Puits Ø 9m
BA1
Neutrino Factory
Debut pente TT10
GOLF
Alt 401.00
SPS
Tunnel LHC
Practice
Foot
Rugby
Neutrinos
TT60
TT2a
193

PS2 integration

Commissioning strategies

- **PS commissioning from PS complex**
  - Protons from PS to PS2 via TT10 and PS2 and fast injection channel for ions (needs upgrade to take 4 GeV beams).
  - In parallel to proton operation from PS complex to SPS

- **PS commissioning from SPL**
  - Commissioning of H- injection
  - Could be done after ring commissioning with protons from PS to reduce complexity.

General requirements on RF system

- **RF system must provide:**
  - **Proton acceleration**
  - **Ion acceleration**
  - **LHC bunch spacings**
  - **Beam compatible with SPS fixed target operation**

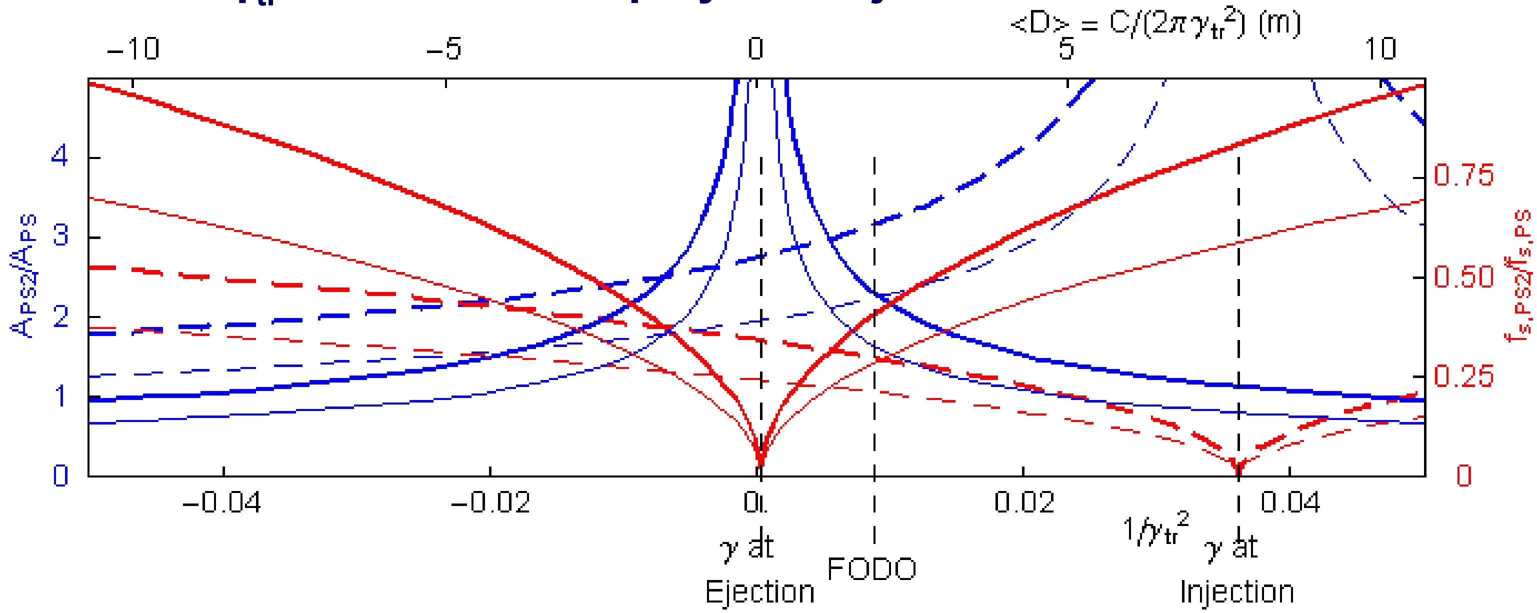
- **Frequency ranges**
  - **Protons: revolution frequency ratio in PS: 1,094 (10% tuning)**
  - **Protons: revolution frequency ratio in PS2: 1,024 (3% tuning)**
  - **Pb54+ ions revolution frequency ratio in PS&PS2 with injection directly from LEIR at 4.8 Tm: 2,7 (300% tuning range)**
  - **Pb54+ ions revolution frequency ratio in PS&PS2 with injection directly from upgraded LEIR at 6.7 Tm: 2,1 (210% tuning range)**
    - Injection field 670 G for ions, 1650 G for protons

Basic rf options

- **10 MHz system**
  - **Emulation of PS 10 MHz system**
    - Tuning range > 3 (3 MHz – 10 MHz), covers ion frequency range
    - Many harmonics for p-acceleration
    - Additional systems needed (20 and 40 MHz) for producing LHC type bunch patterns (25 and 50 ns) and shortening → rf gymnastics needed!
- **40 MHz system**
  - **Motivated by (LP) SPL providing 0.5 ms (1 ms) quasi-continuous H^- beam 352 MHz, ~1.4E14 per pulse with chopping at 40 MHz.**
    - Any LHC bunch pattern up to 40 MHz via chopping at injection
    - Minimizes rf gymnastics in PS2.
    - Question on possible tuning range (in particular for ions)
    - Bucket length limitation of 25 ns (50 ns with tuning range of factor 2)
      - Special schemes for ions, limited performance for single bunch (nTOF)
      - E-cloud issues in the PS2 with 40 MHz from injection?

Impact of rf on lattice design

- **The increase of working range (PS: 1.4 -> 26GeV, PS2: 4 -> 50GeV):**
  - **Slows down longitudinal motion while increasing acceptances**
  - **Impacts on RF gymnastics → impact on cycle time**
- **Choice of γ_{tr} and the lattice plays a major role:**



Acceptance (blue) **and** **adiabaticity (red)** **ratios PS2/PS** at injection (dashed) and **ejection (solid)**

keeping RF Voltages of present PS (thin lines) and **doubling gradients (thick lines)**

Lattice options and investigations

- **RF considerations favour:**
  - **Small absolute values of γ_{tr} for reasonable duration of rf gymnastics (adiabaticity) and reasonable voltages at high energy**
  - **Typical range of $8 < \gamma_{tr} < 12$ seems appropriate**
    - Range can be relaxed depending on choice of rf
    - No high energy gymnastics in 40 MHz scenario
- **Regular FODO**
  - **For a machine length of ~twice PS with similar optical behaviour the "natural" value of γ_{tr} is in the range specified above.**
  - **Such a lattice requires a transition crossing**
- **Search for lattices with imaginary γ_{tr}:**
  - **Avoids transition crossing**
  - **More complicated lattice design and more magnet types/families**

Performance of PS2

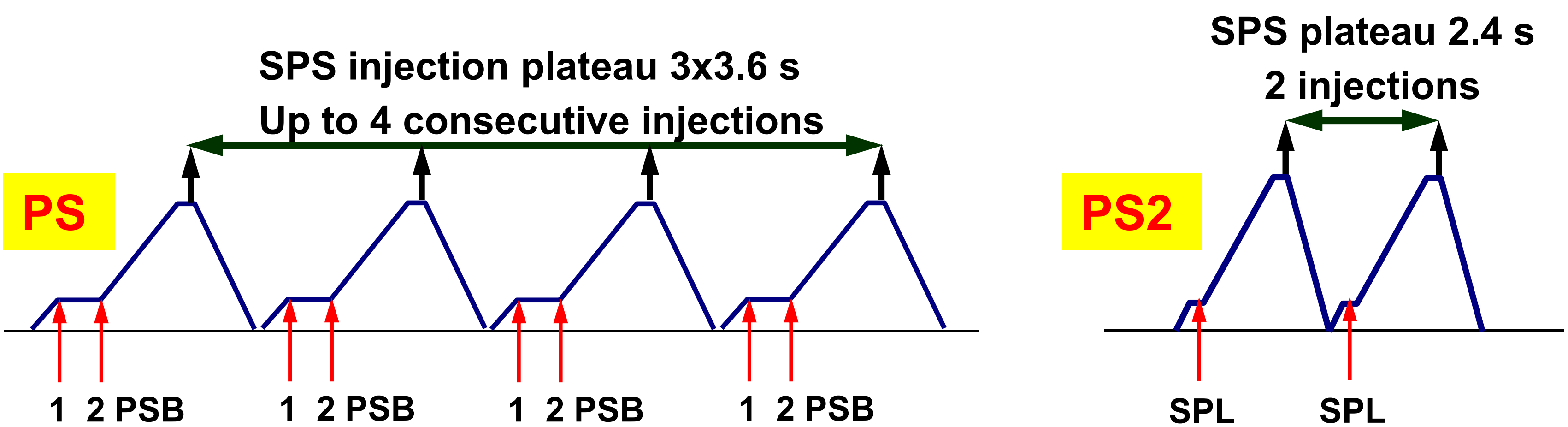
- **Twice average line density of PS**
- **Twice longer machine**
- **Twice extraction energy**
- **Identical acceleration time**

Theoretically factor 8 increase in power (assuming identical normalised emittances)

- **Shorter cycle time in some cases (LHC without double batch)**
  - **Basic machine cycle of 2.4 s with fast (CT) extraction at 50 GeV.**
  - **Physics cycle with 3.6 s with slow extraction at 50 GeV (phyics duty cycle 1/3)**

LHC beams

- **Example 25 ns beam (SPL injector):**
  - **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)
    - Accordingly reduced flat bottom with beam in LHC (35% reduction).



LHC beam from PS2

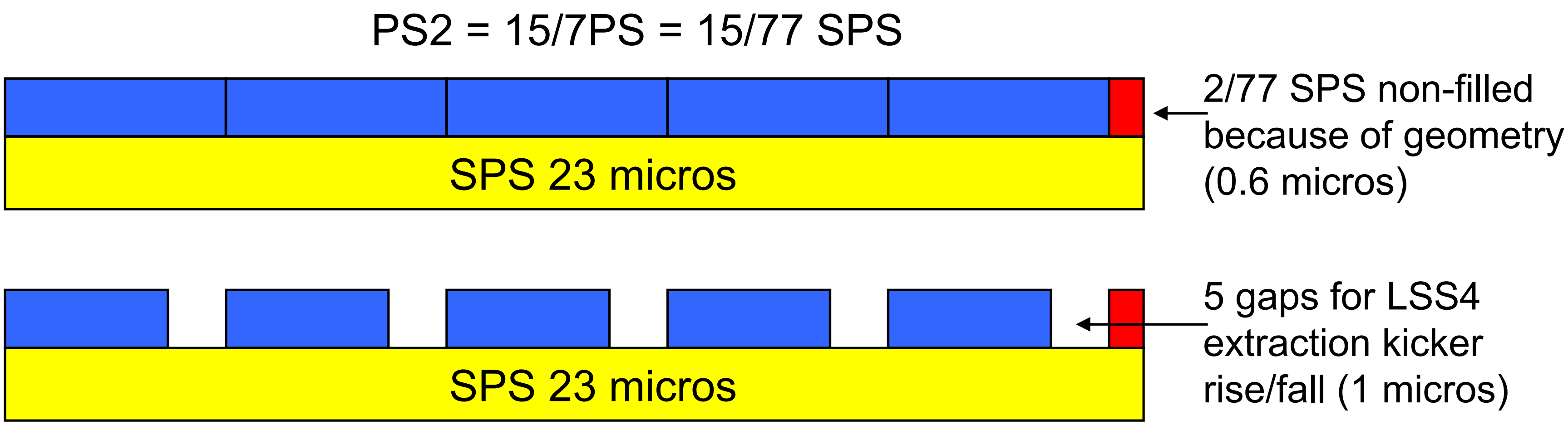
- **Nominal bunch train at extraction (independent of rf route)**
  - **h=180 (40 MHz) with bunch shortening to fit SPS 200 MHz.**
  - **168 buckets filled leaving a kicker gap of ~ 300 ns (50 GeV!)**
    - Achieved by 42 filled buckets on h=45 (10 MHz) and 4 splittings
    - Alternatively with painting in 40 MHz directly from SPL (would allow up to 170 bunches)
    - No strong impact on LHC filling scheme (P.Collier)
- **Any other bunch train pattern down to 25 ns spacing**
  - **Straightforward with SPL 40 MHz chopping and 40 MHz system**
  - **Limited to present schemes (75 ns, 1, 12, bunches etc…) with 10 MHz system and "classical" splitting.**

High-intensity physics beams

- **SPS fixed target beam:**
  - **PS2 will provide twice line density of PS high-intensity FT beam**
  - **Twice circumference gives up to 4 times more intensity**
    - ~1.2E14 per PS2 cycle
  - **Five-turn extraction will fill SPS with single shot instead of 2 from PS**
    - Twice more intensity in SPS via twice higher line density.
    - No injection flat bottom in the SPS
  - **Clean bunch to bucket transfer PS2 40 MHz to SPS 200 MHz (cf. LHC)**
    - ~7E11 protons per PS2 40 MHz bucket
    - Reduced by factor 5 to ~1.7E11 in 1 out of 5 SPS 200 MHz buckets
  - **Transverse emittances: like upper limits of present CNGS beam**
    - Norm. sigma emittances 15/8 mm mrad (h/v)
    - Adiabatic emittance damping at 50 GeV by $(\beta\gamma)_{13} / (\beta\gamma)_{50} = 0.27$
    - Therefore ~1/2 present beamsize due to emittance.

CNGS-type upgrade beam from PS2

- **Filling the SPS with 5 turns from PS2**



  - **Filling is achieved in a single PS2 pulse 17.4 out of 23 micros**
  - **Extraction kicker gap corr. to ~40 unfilled 40 MHz buckets.**
    - Straightforward with SPL
    - 9 (36) or 12 (48) missing bunches at injection on h=45 (180) i.e. 10 (40) MHz
    - ~140 filled 40 MHz buckets in PS2

Summary

- **Design goals for PS2**
- **Reasoning for parameter and design choices for PS2**
- **Beam performances for main users**

- **Thanks to all PS2 WG members and all colleagues that contributed to the study**

PS2 preliminary parameters

Parameter	unit	PS2	PS
Injection energy kinetic	GeV	4.0	1.4
Extraction energy kinetic	GeV	~ 50	13/25
Max. intensity LHC (25ns)	ppb	4.0×10^{11}	1.7×10^{11}
Max. intensity FT	ppp	1.2×10^{14}	3.3×10^{13}
Max. stored energy	kJ	1000	70
Linear ramp rate	T/s	1.5	2.2
Repetition time (50 GeV)	s	~ 2.5	1.2/2.4
Max. effective beam power	kW	400	60

Backup slide: LHC beam from PS2 (ii)

- **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 microm (identical to PS)**
  - **Longitudinal emittance varying with intensity**
- **Longitudinal aspects**
  - **Scale longit. emittance with sqrt of intensity $\varepsilon = \varepsilon_0 \sqrt{(I/I_0)}$**
    - (for stability in SPS, Elena)
    - **I max = 4E11 → ε max** = 0.35 eVs*√(4/1.3) = **0.6 eVs**
  - **Momentum spread scales like emittance (bunch length = const.)**
    - Scaling from nominal beam dp/p=2E-3 but @50 GeV dp/p=1E-3!
    - **dp/p max** = 1E-3*√3 = **1.8 → no aperture issues**
  - **Voltage at PS2 extraction scales like intensity (emittance^2).**
    - 3 times more voltage for shortening of the 4E11 bunch.

Back-up slide: Optics constraints for PS2 ring

Basic beam parameters	PS	PS2
Injection kinetic energy [GeV]	1.4	4
Extraction kinetic energy [GeV]	13/25	50
Circumference [m]	200π	1346
Transition energy [GeV]	6	8-12(i)
Dipole function type	Combined	Separated
Dipole length [m]	5	3-4
Maximum bending field [T]	1.2	1.8
Maximum quadrupole gradient [T/m]	5	17
Maximum beta functions [m]	23	60
Maximum dispersion function [m]	3	6
Minimum drift space for dipoles [m]	1	0.5
Minimum drift space for quads [m]		0.8
Layout	Circle	Racetrack
Maximum arc length [m]		~510

- Incoherent space charge tune-shift $\Delta Q_{sc} \propto \frac{N_b}{\epsilon_n \beta \gamma^2 B_f} < 0.2$
- Improve SPS performance
- Analysis of possible bunch patterns: $C_{PS2} = (15/77)\ C_{SPS} = (15/7)\ C_{PS}$
- Time for bunch splitting with 10MHz RF systems
- Operational flexibility and low cost
- Normal conducting magnets
- Aperture considerations for high intensity SPS physics beam
- Space considerations
- Long straight section minimum length for injection and extraction elements