PS2 Design Optimization

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for the PS2 Working Group

Contents

Plans for future injectors: Motivation

1. Improve reliability and reduce vulnerability of injector chain for LHC era:

   Ageing accelerators (PS is 49 years old!) operating far beyond initial parameters

   ⇒ need for new accelerators designed for the needs of SLHC

2. Remove injector performance limitations:

   Excessive incoherent space charge tune spreads ΔQ_{SC} at injection in the PSB (50 MeV) and PS (1.4 GeV) because of the high required beam brightness N/ε^*.

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

with N_b : number of protons/bunch

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

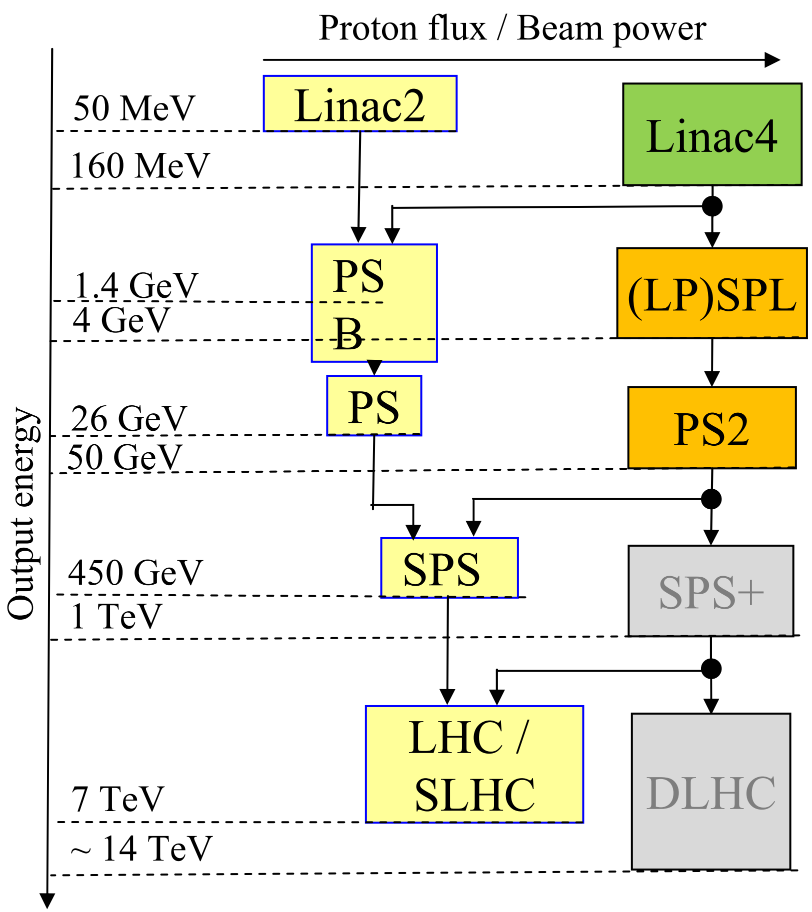
R : mean radius of the accelerator

$\beta\gamma$: classical relativistic parameters

⇒ need to increase the injection energy in the synchrotrons

- Increase injection energy in the PSB from 50 to 160 MeV
- Design the PS2 (PS successor) with an acceptable space charge effect for the maximum beam envisaged for SLHC.
- Increase injection energy in the SPS from 25 to 50 GeV kinetic

CERN injector complex upgrade - Overview



Linac4: H- Linac
(160 MeV)
(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)

Stage 1: Linac4
- construction 2008 – 2014

Stage 2: PS2 and SPL: preparation of Conceptual Design Reports for
- **project approval mid 2012**
- **start of construction begin 2013**

PS2 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 PS2 and complete complex
  - Potential for future upgrades of the accelerator complex

Performance requirements and parameters

- **Starting point for the design is brightness (N/ε_n) for LHC beams**
  - Design goal: Twice higher brightness than "ultimate" 25ns beam with 20% intensity reserve for transfer losses
    - 4.0×10^{11}ppb = $2 \times 1.7\times10^{11} \times 1.2$ in transverse emittances of 3μm
- **Injection energy**
  - Determined by the beam brightness of the LHC beam
  - Limiting the incoherent space charge tune spread at injection to below 0.2 requires
    - 4 GeV injection energy
- **Extraction energy**
  - Injection into SPS above transition energy to reduce space charge effects
  - Higher energy gives smaller transverse emittances and beam sizes and therefore reduced losses
  - Potential for long-term SPS replacement with higher energy
    - ~50 GeV extraction energy

PS2 machine size

- **Constraints from desired extraction energy ~50 GeV**
  - **Iron dominated dipoles aiming at B ≤ 1.7 T**
    - **PS2 will have roughly twice PS size i.e. R ~ 200 m and C ~ 1250 m.**
- **Constraints from filling SPS for physics**
  - **Complete filling of SPS circumference is desired for high intensity physics**
  - **Using a 5-turn multi-turn extraction scheme, similar to PS (2 x 5 turns):**
    - **Ideal PS2 length is 1/5 SPS = 11/5 PS = 2.2 PS.**
- **Constraints from PS2-SPS synchronisation (rf cogging)**
  - **N x h_{PS2} = K x h_{SPS} is needed for correct synchronisation**
    - **(N/K) = 77/15 is best choice (5 PS2 slightly shorter than the SPS.)**
    - h (200MHz SPS) = 4620, h (40MHz SPS) = 924, h (40MHz PS2) = 180
- **Optimum length for PS2 from above arguments**
  - **PS2 = 15/77 SPS = 15/77 * 11 PS = 15/7 PS.**
    - **1346.4 m circumference, 214.3 m average radius**

PS2 main parameters

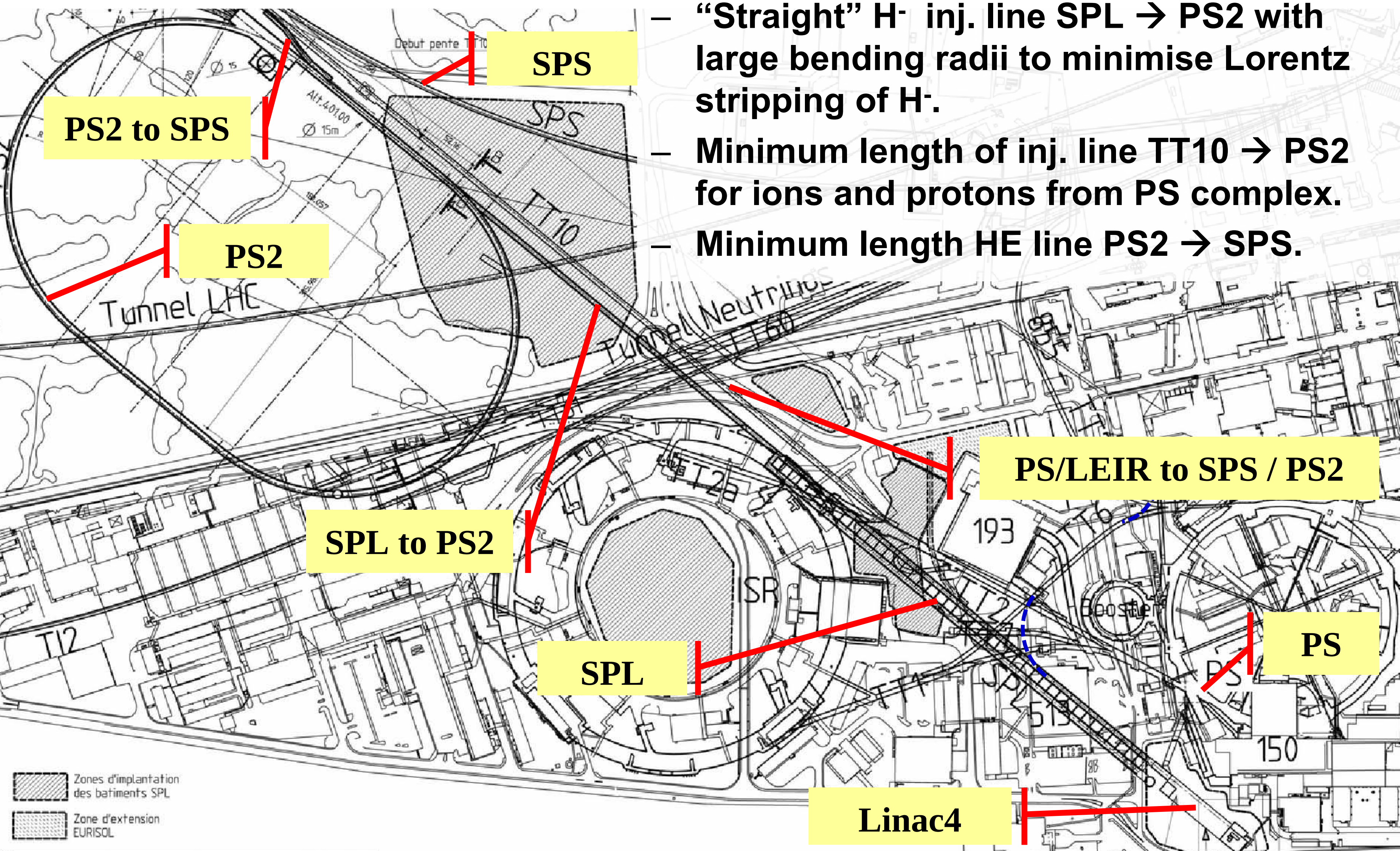
Parameter	unit	PS2	PS
Injection energy kinetic	GeV	4.0	1.4
Extraction energy kinetic	GeV	20 - 50	13 - 25
Circumference	m	1346	628
Max. bunch intensity LHC (25ns)	ppb	4.0×10^{11}	1.7×10^{11}
Max. pulse intensity LHC (25ns)	ppp	6.7×10^{13}	1.2×10^{13}
Max. pulse intensity FT	ppp	1.0×10^{14}	3.3×10^{13}
Linear ramp rate	T/s	1.5	2.2
Repetition time (50 GeV)	s	~ 2.5	1.2/2.4
Max. stored energy	kJ	800	70
Max. effective beam power	kW	320	60

PS2 integration and machine shape

- **Integration requirements**
  - H^- Injection from LPSPL
  - Injection of ions from LEIR via TT10 transfer line
  - Injection of protons from PS complex viaTT10 for commissioning
  - Extraction towards the SPS via TT10
- **Region at end of TT10 transfer line from PS to SPS was identified as optimum location for PS2**
- **Machine shape**
  - Optimisation leads towards a racetrack shape
  - Two compact arcs and two long zero-dispersion straight sections
  - One long straight section for all injection and extraction systems
  - Second long straight section dedicated for RF and collimation

PS2 integration

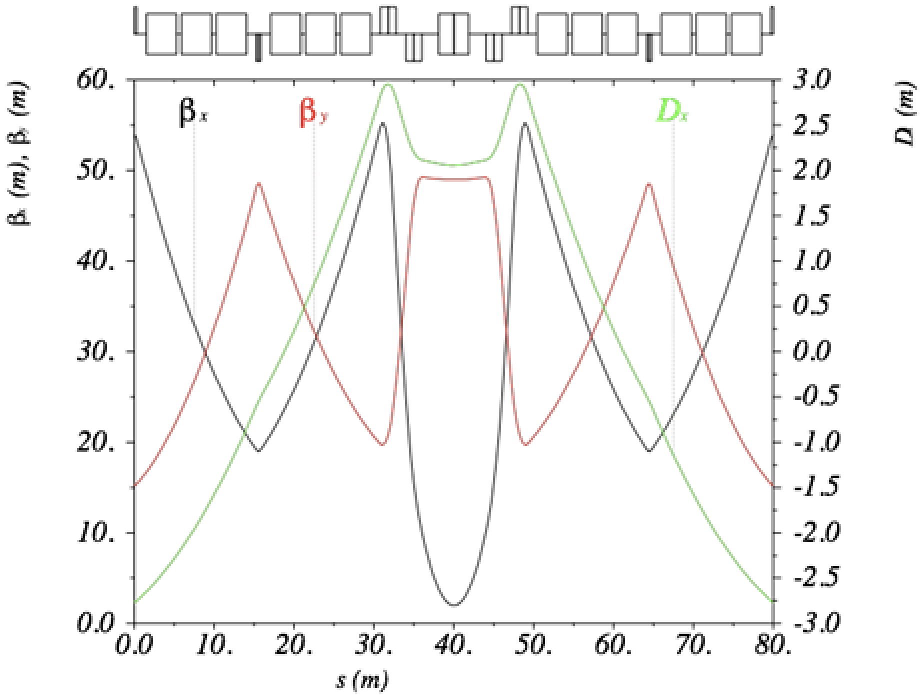
– "Straight" H^- inj. line SPL → PS2 with large bending radii to minimise Lorentz stripping of H^-.
– Minimum length of inj. line TT10 → PS2 for ions and protons from PS complex.
– Minimum length HE line PS2 → SPS.



PS2 lattice design

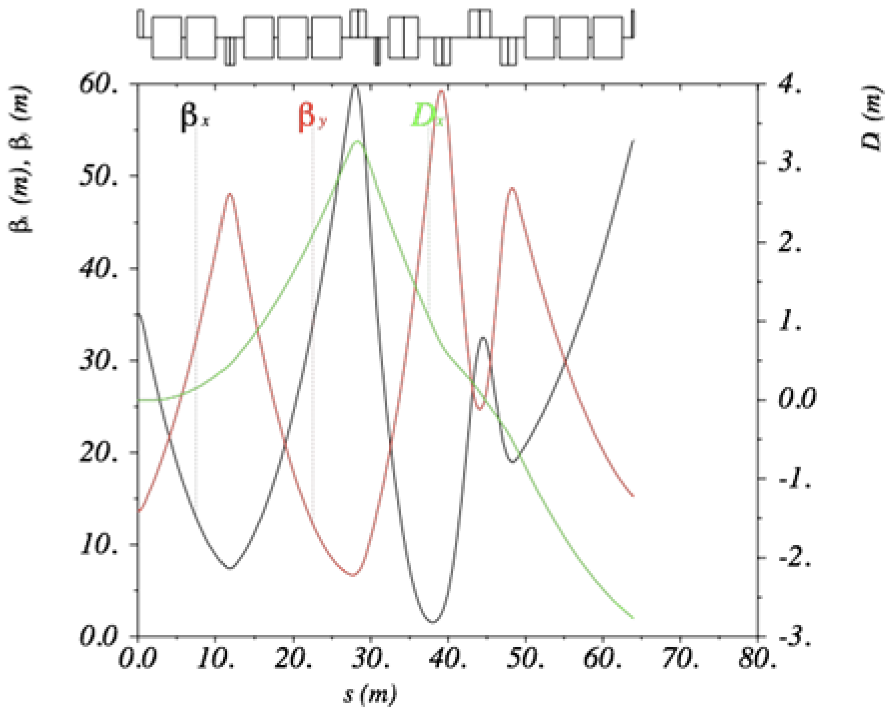
- Lattice with imaginary γ_{tr}
  - No transition crossing
    - No beam losses at transition
    - Simplification for operation by avoiding transition jump scheme
  - More complicated lattice design and more magnet types/families than in e.g. regular FODO lattices
- Lattice structure
  - Injection/extraction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

PS2 NMC module and dispersion suppressor



- **NMC module with** γ_t of **26i** and phase advances of **267.4°** and **157.3°.**
- 2 FODO cells with 3 + 3 bends and a low-beta doublet and 1 bend in centre

- **Dispersion suppressor module**
- Similar half module as NMC with **2+3+1** dipoles for D- suppression and matching cell with **3** dipoles



PS2 NMC ring lattice

Transition gamma: 37i

Tunes: 13.25 / 8.25 (h/v)

Beta max: 59 m (h and v)

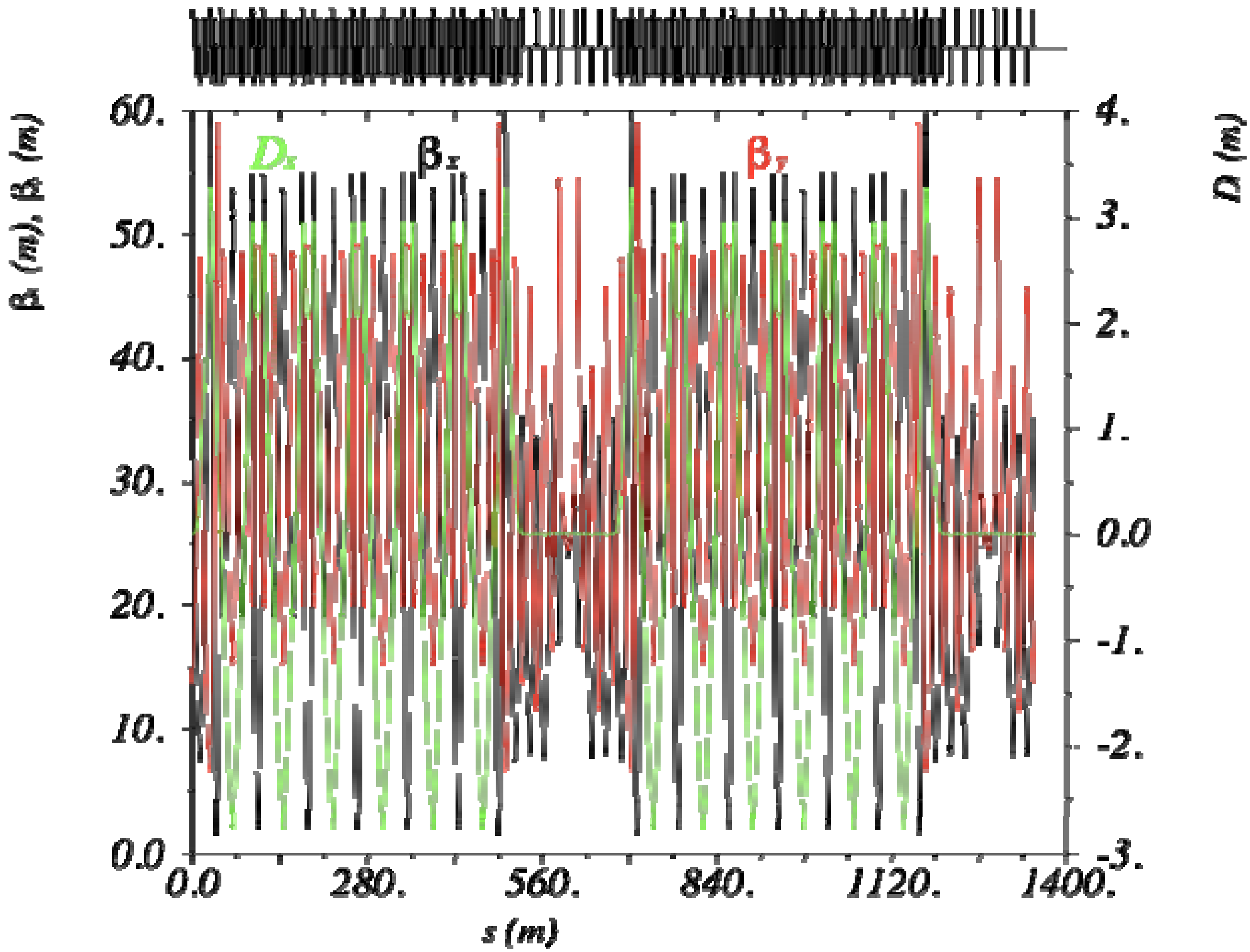
Dispersion min.: -2.8 m
Dispersion max.: 3.3 m

Relative chromaticities
-1.65 / -1.59 (h/v)

Circumference: 1346.4m

166 dipoles, 3.78m long (1.7T field)

132 quadrupoles in 4+6+7 = 17 families of 5+1 types (lengths and apertures), with max. gradient of 0.1 Tm^{-2}
Not yet optimized



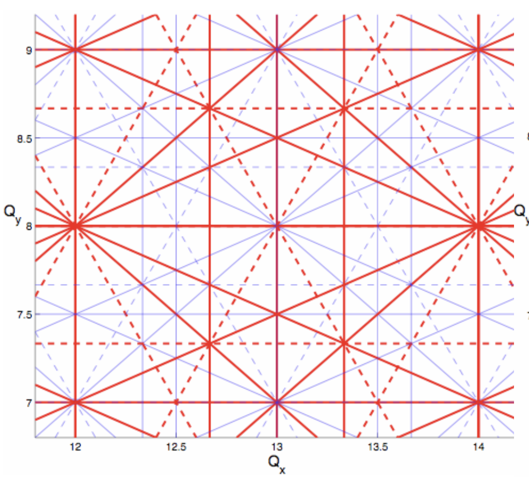
Alternative investigations - 3-fold NMC ring

- **Racetrack corresponds best to requirements but has low symmetry of 2.**
- **Higher (3-fold) symmetry is advantageous for structure resonances and working point choice but not compatible with present injection/extraction concept.**
- **Further investigations on working point optimization and structure resonances.**

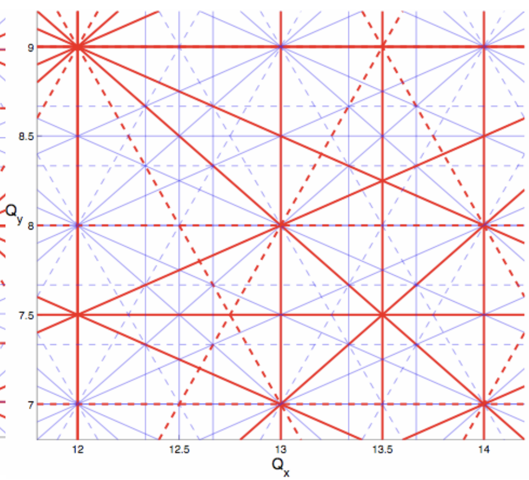
Super-periodicity of 2 versus 3

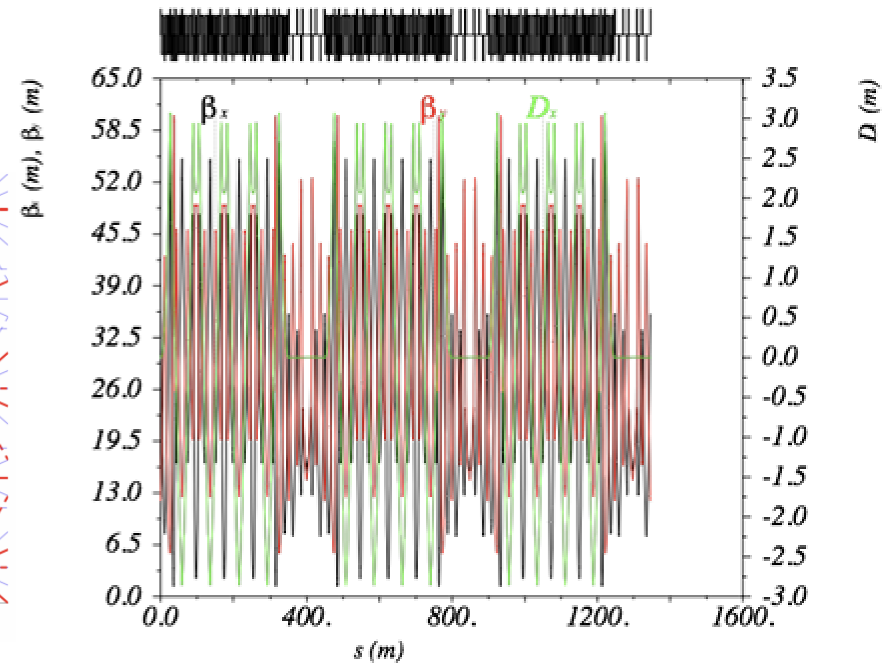
Systematic (red) and random (blue) resonances
for $12<Q_x<14$ and $7<Q_z<9$

Two fold symmetry



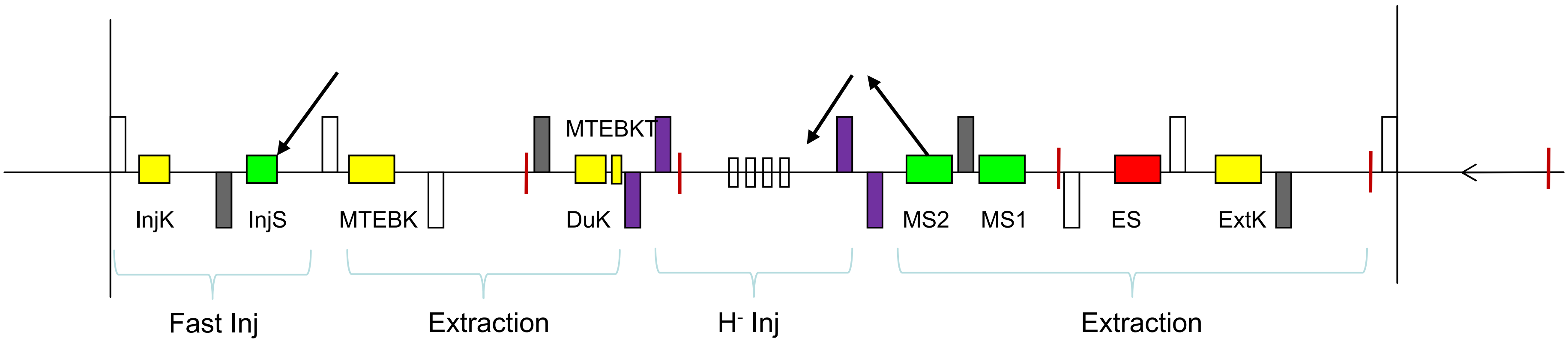
Three fold symmetry





Long injection/extraction straight section

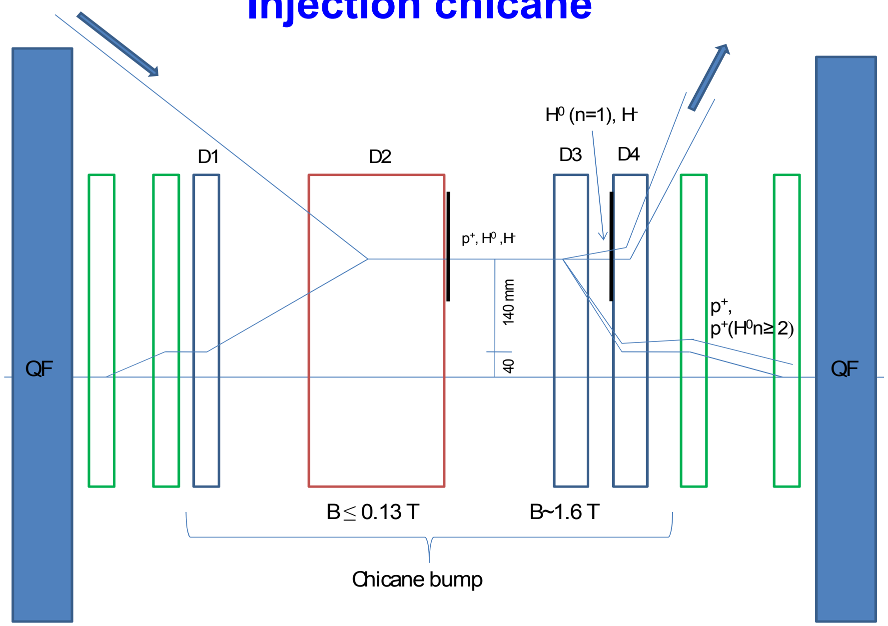
- **Regular FODO with ~90 deg hor phase advance, zero dispersion.**
- **Split-triplet insertion in the centre, to house H- injection**



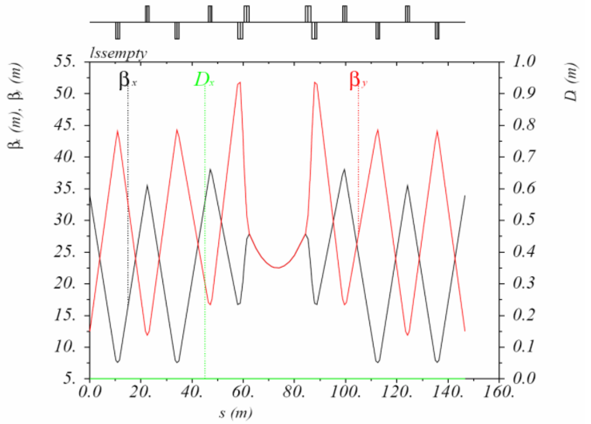
- **Common usage of single channel for all extractions**
  - **Fast extraction to SPS (LHC beams)**
  - **Multi Turn Extraction (MTE – five turns) to SPS for fixed target physcis**
  - **Slow extraction (if required) for physics at PS2**
    - Minimisation of equipment and machine impedance and space requirements

H⁻ injection

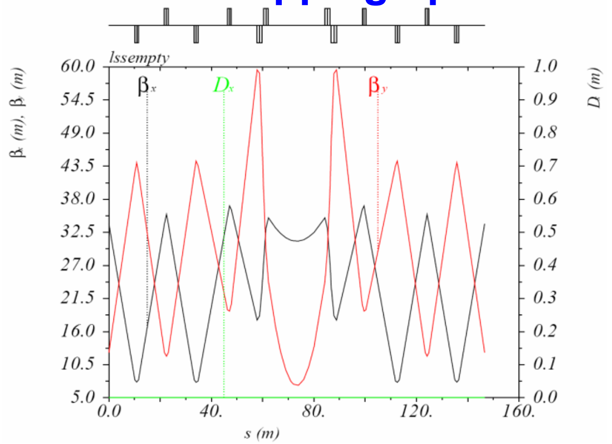
Injection chicane



Foil stripping optics



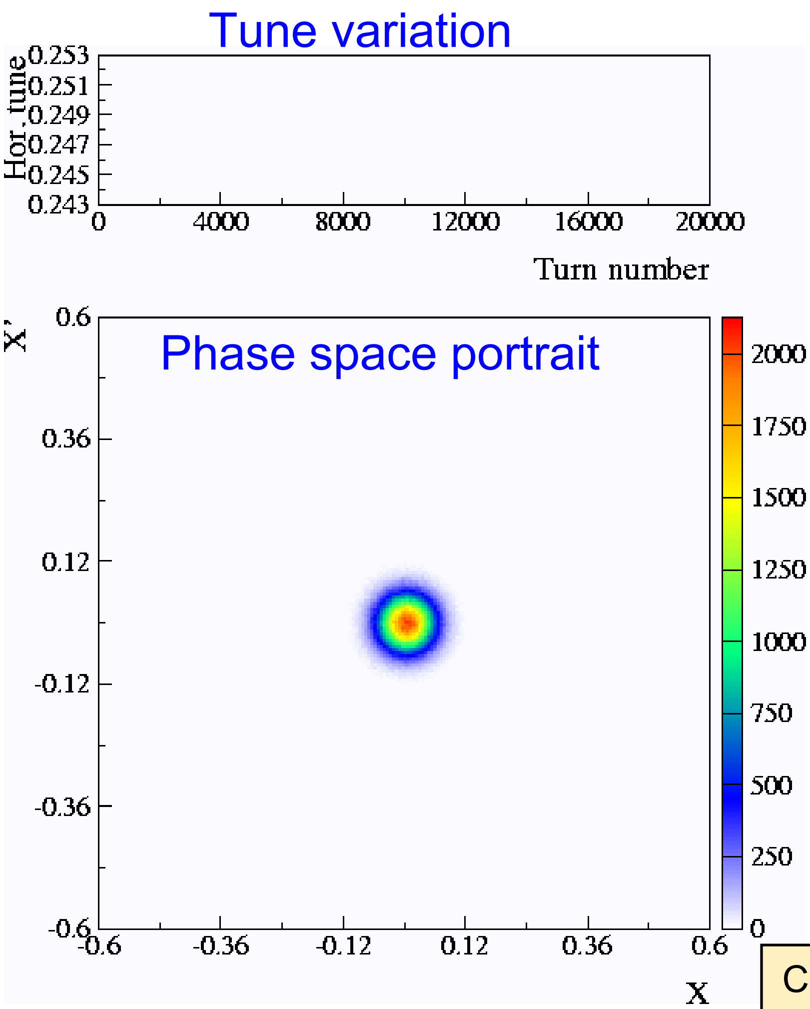
Laser stripping optics



- **Baseline is classical foil stripping with fast horizontal and vertical orbit bumpers for corr./uncorr. painting.**
- **Optimisation of insertion layout and optics to allow also integrating laser stripping.**
  - **Collaboration with LARP and US Labs**

PS – Multi Turn Extraction: principle, simulations

- **Fourth-order tune 0.25 or 0.75**
  - **4th order phase space topology**
  - **Splitting of beam in 5 "islands" with sextupoles/octopoles**
    - Loss-less splitting
- **Extraction process**
  - **Closed extraction bump taking the outer islands into the extraction channel**
    - Similar to slow extraction
  - **Outer island are extracted on four consecutive turns**
  - **Central island as fifth turn with an additional kicker**
    - No losses with beam gap for kicker rise time.



Simulation parameters:

Hénon-like map (i.e. 2D polynomial – degree 3 - mapping) representing a FODO cell with sextupole and octupole

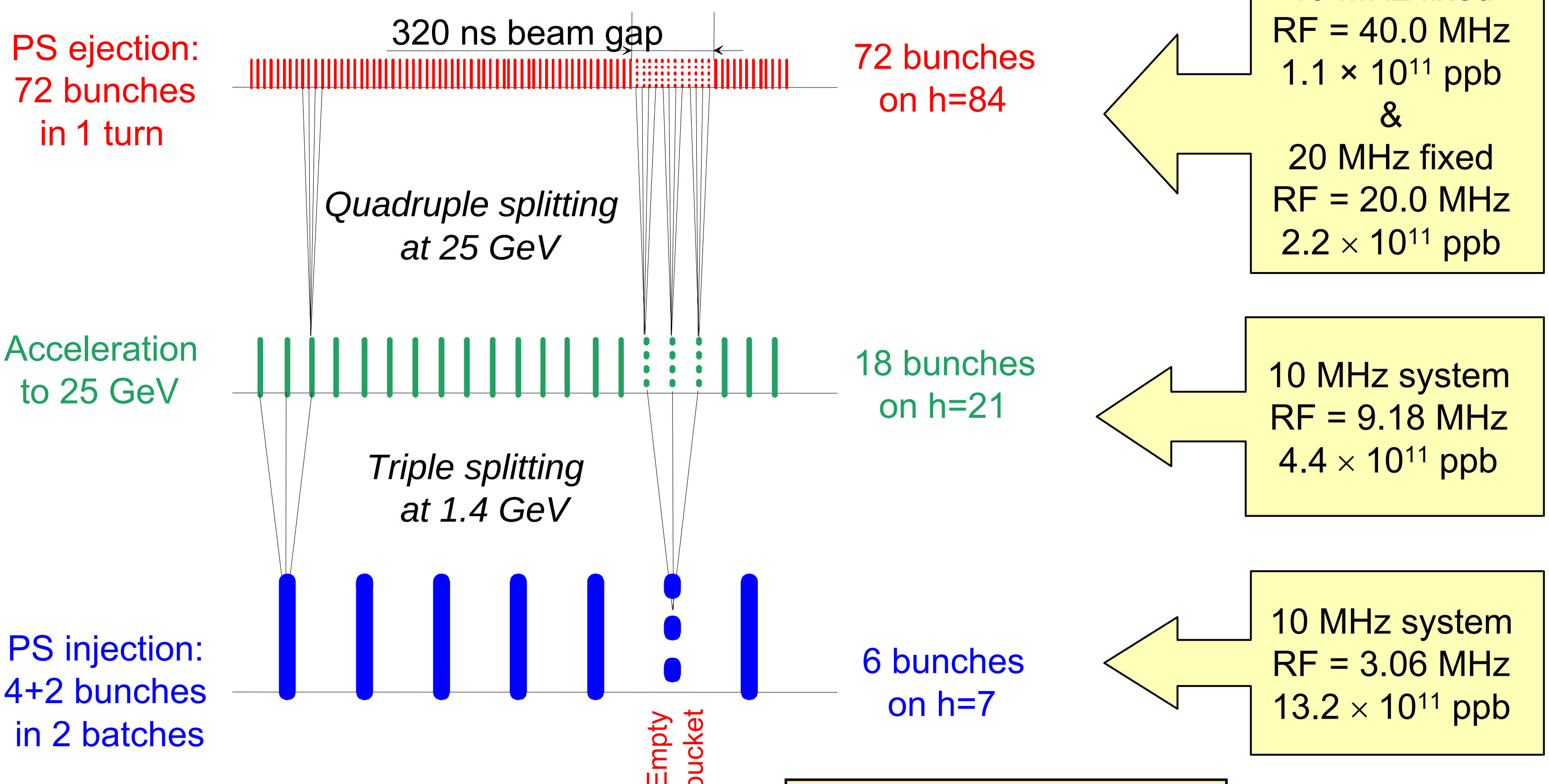
Courtesy: M. Giovannozzi

PS2 RF system

- **RF system requirements:**
  - **Proton acceleration: revolution frequency ratio : 1,024 (3% tuning)**
  - **Pb54+ ions revolution frequency ratio in PS&PS2 with injection directly from *upgraded LEIR* at 6.7 Tm: 2,1 (110% tuning range)**
  - **All LHC bunch spacings and patterns and beams for SPS operation**
- **Preferred RF option**
  - **Tuneable 40 MHz system (18 – 40 MHz)**
    - Motivated by (LP) SPL 40 MHz chopping that will allow direct painting of any LHC bunch pattern up to 40 MHz already at injection
    - **Minimizes rf gymnastics in PS2 and RF systems (→impedance reduction, space requirements, simplified operation)**
  - **Feasibility of tuneable 40 MHz system (>octave) to be demonstrated**
    - R&D program for PS2 RF system being launched.
    - Based on perpendicularly biased ferrites.
- **Beam structure of 40 MHz is likely to provoke e-cloud effects all along the cycle**
  - **Countermeasures at vacuum system level will be needed**

LHC beam production in PS

- **Complicated longitudinal gymnastics to obtain identical bunches for LHC**
  - **Triple splitting at injection and two double splittings before extraction**



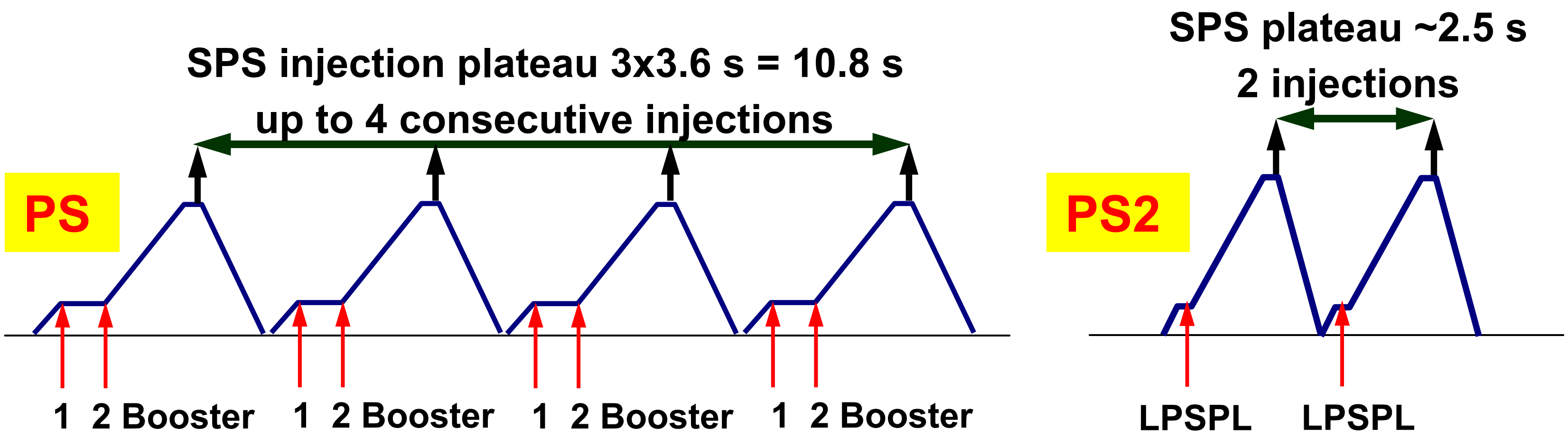
Courtesy: R. Garoby

LHC beam 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.
- **Any other bunch train pattern possible down to 25 ns spacing**
  - **Straightforward with SPL 40 MHz chopping and 40 MHz system**
    - (Would be limited to present schemes (75 ns, 1, 12, bunches etc…) with a 10 MHz RF system and "classical" splitting.)
- **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 micron (identical to PS)**

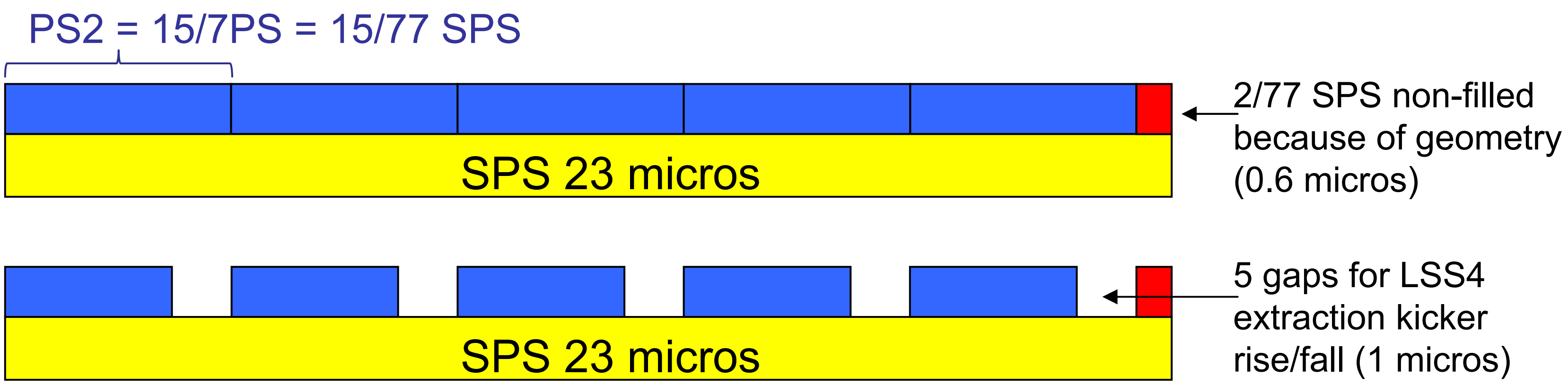
LHC beam from PS2 (ii)

- **Example 25 ns beam from LPSPL – PS2:**
  - **Only 2 injections (instead of 4) from PS to fill SPS for LHC**
  - **PS2 cycle length 2.5 s instead of 3.6 s for PS**
    - Reduces SPS LHC cycle length from **21.6** to **13.3 s** (gain 3x3.6 – 1x2.5)



High intensity physics beam for SPS

- **PS2 provides up to twice line density of PS high-intensity beam**
- **Twice circumference gives up to~4 times more intensity in total**
  - ~1.0E14 per PS2 cycle
- **Five-turn extraction will fill SPS with single shot instead of two from PS**
  - End up with twice more intensity in SPS than at present
  - No injection flat bottom in the SPS (two shot filling from PS presently)
- **Clean bunch to bucket transfer PS2 40 MHz to SPS 200 MHz (cf. LHC)**
  - ~6E11 protons per PS2 40 MHz bucket → 1.2E11 in every 5th SPS 200 MHz bucket



Summary

- PS2 main parameters are defined, based on LHC requirements
- Design optimised for integration in the existing and future CERN accelerator complex
- Preferred options for lattice, RF concept, injection and extraction layout have been identified
- Goal is to provide a conceptual design report for approval by mid 2012 and project start in 2013

- Thanks to all PS2 WG members and all colleagues in LARP and in other labs for contributing to the design study