Alternative/complementary Possibilities

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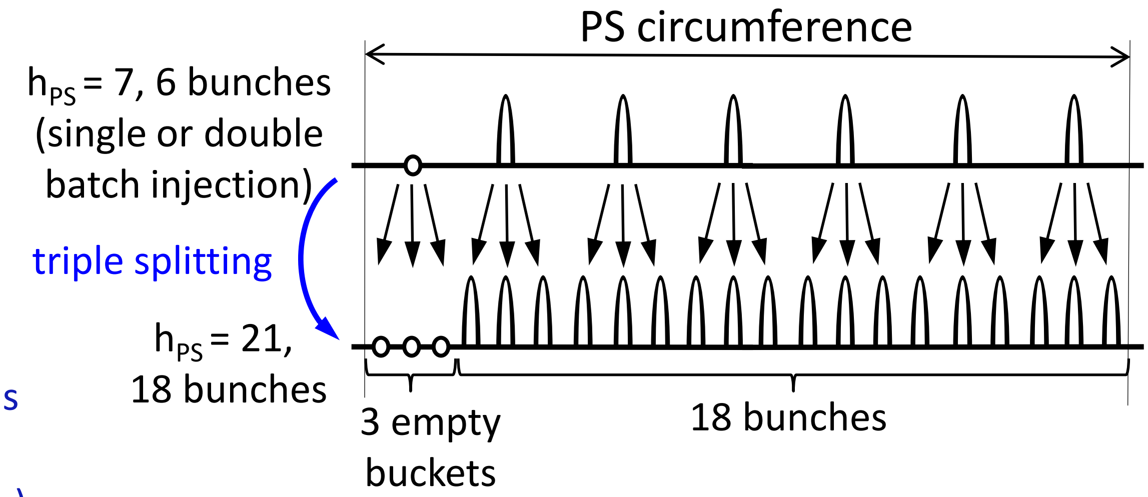
- Introduction
  - Present PS scheme for nominal LHC bunch trains
  - Alternative/complementary Scenarios
- Batch Compression schemes in the PS
  - Filling 8 out h_{PS}=8 or h_{PS}=9 PS buckets?
  - Compression to h_{PS} = 10 and generation of 64 bunches
  - Compression to h_{PS} = 14 and generation of 48 bunches
- RCS as new PS Injector
- Summary and Outlook

Introduction
PS scheme for LHC bunch trains

- Present PS scheme (end of the 1990ies)
  - Acceleration to flat-top with h_{PS}=21
  - One or two double splitting at flat-top for 50 ns or 25 ns trains
  - No debunching/rebunching at flat-top (to avoid instabilities)
- (75 ns LHC beams with double splitting injection energy, h_{PS}=14 acceleration)



RF gymnastics at injection energy for 25 ns and 50 ns LHC bunch trains

- Scheme to use all four Booster rings (and single PSB to PS transfer) without batch compression or extension
  - Factor 7 in PS harmonic at injection
  - Proposed (R.Garoby and M.Benedikt):
    - Three bunches per PSB ring fill 12 out of h_{PS}=14 PS buckets
    - Implementation difficult:
      (i) short kicker rise times and
      (ii) generation of three bunches in the PSB with unequal spacing

Introduction
Alternative/complementary Scenarios

- Scenarios presented here:
  - ➠ Alternative/complementary to extrapolation of present scheme to higher brightness using Linac4 and PSB 2 GeV upgrade
  - Batch compression in the PS to increase brightness after acceleration to a suitable energy
    - ➠ Abandon factor 7 in PS harmonics to (i) use all four PSB rings (with singe batch transfer) and (ii) use batch compression to increase brightness
    - Fill as much as possible of the PS circumference at injection
    - Batch compression after first acceleration to an appropriate energy
    - ➠ Reduced number of bunches per PS cycle -> Higher intensity per bunch and, thus, brightness
  - Short Rapid Cycling Synchrotron (RCS) as new PS injector

- General considerations
  - Transverse direct space charge effects assumed the dominant limitation
  - Possible brightness scaled from 1993 design for LHC beams in PS
    - No gains assumed (conservatively) from single batch PS filling (short flat bottom)
  - Intensity estimates per LHC 25 ns bunch, 2.5 μm transverse rms emittance out of PSB
    - Smaller emittance beams with intensities reduced by the same factor
    - For LHC 50 ns beams, larger intensities possible (by a factor probably <2!)

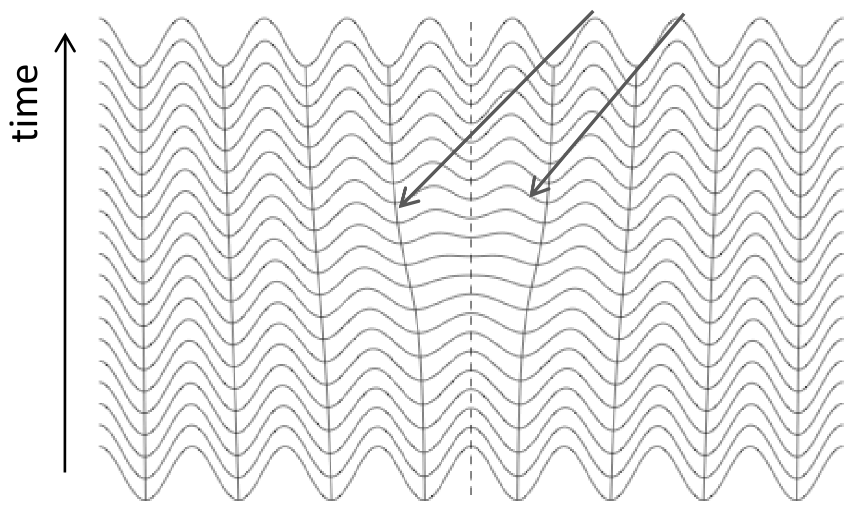
Batch Compression Schemes in the PS
Insertion of an empty bucket with fully filled h_{PS}=8 PS

- Batch compression (or extension) works well:
  - With a partially filled machine (conflicts with aim to fill most of circumference at injection)
  - Low harmonic numbers reducing number of harmonic number changes (aspect in favor of h_{PS} = 4 or h_{PS} = 5 …. discarded due to large acceptances and low frequencies)

- Is h_{PS} = 8 to h_{PS} = 9 compression with eight bunches feasible?!
  - Simulation presented later with h_{PS} = 10 component to (slightly) allow/facilitate this process
  - RF potential around PS circumference (mountain range of time evolution)

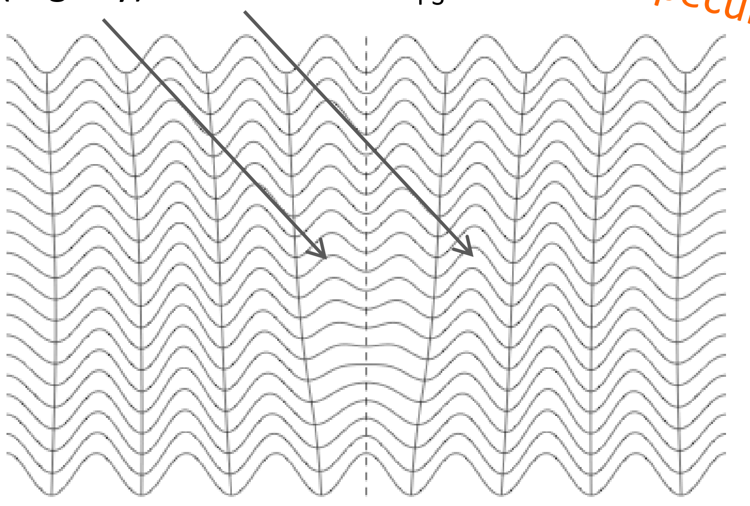
Somewhat speculative

Lack of long. focusing due to beating (slightly) reduced with h_{PS}=10



$V_{RF} = 0.5\, t \sin(9\varphi) - 0.5\,(1-t)\sin(8\varphi)$

Pure transition from h_{PS}=8 to h_{PS}=9



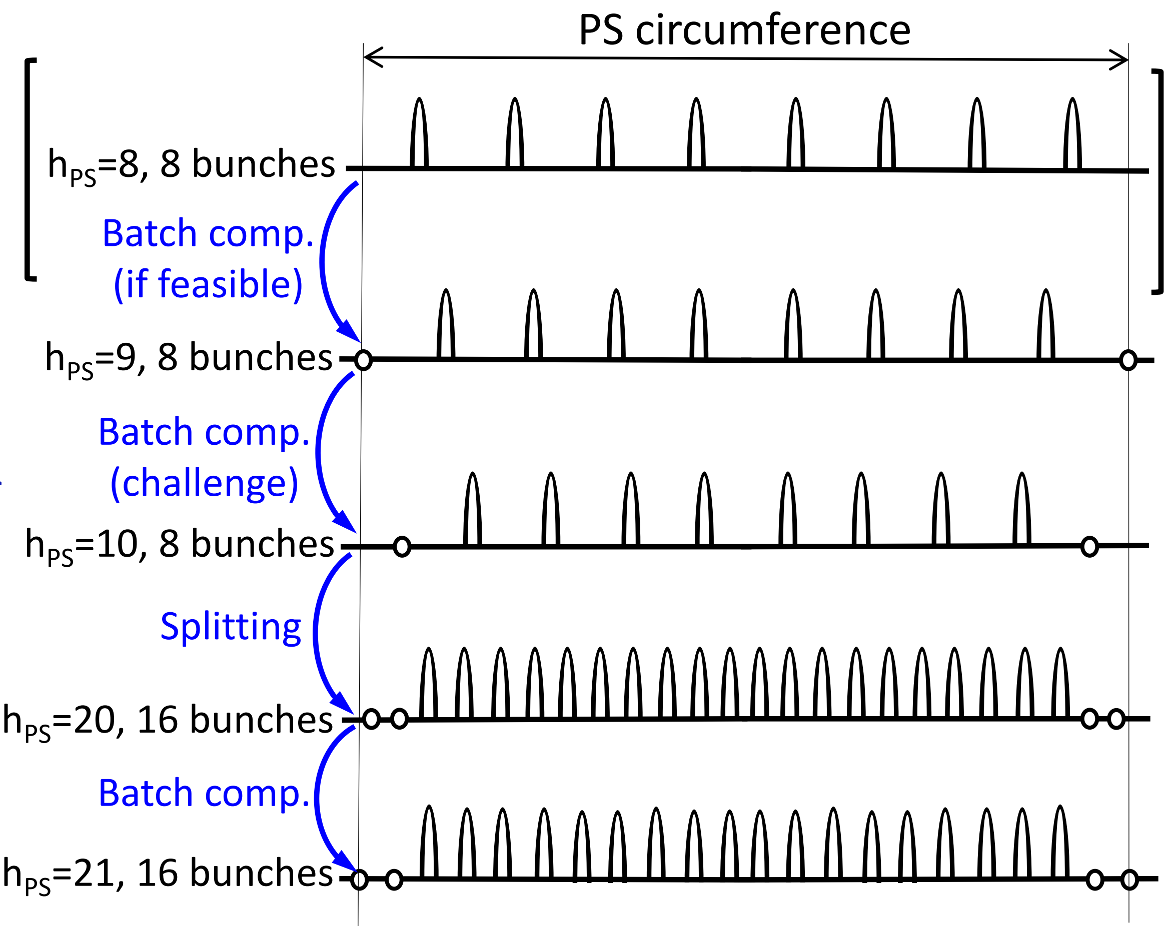
$V_{RF} = -0.4\,(1-t)\sin(8\varphi) + 0.4\, t\sin(9\varphi) + 0.2\left(1-(1-2t)^2\right)\sin(10\varphi)$

Additional h_{PS}=10 (20%) component

Batch Compression Schemes in the PS
Compression to h_{PS} = 10 and generation of 64 bunches

- Injection and first acceleration with h_{PS}=8 or h_{PS}=9
- Potential brightness increase: 12/8 = 1.50*
  - Corresponds to PSB upgrade: 1.4 GeV to 1.77 GeV
  - Brightness per bunch for 25 ns trains out of PSB
    - ε^*=2.5 μm and 2.23 10^{11} or
    - ε^*=1.90 μm and 1.7 10^{11}
- Estimate of longitudinal parameters at injection for 25 ns trains
  - Every bunch split into 8 LHC bunches with 0.35 eVs
  - 1.6 eVs per injected bunch allows a factor 1.75 blow-up

*) With h_{PS}=8 at injection, compared to present situation with Linac2 and double batch PSB to PS transfer



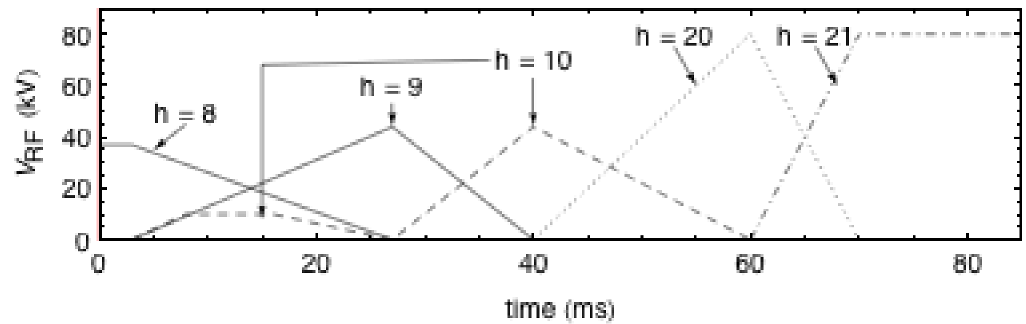
RF gymnastics at an appropriate intermediate energy (hypothesis 2.5 GeV)
(Injection and first acceleration with h_{PS}=8 or h_{PS}=9)

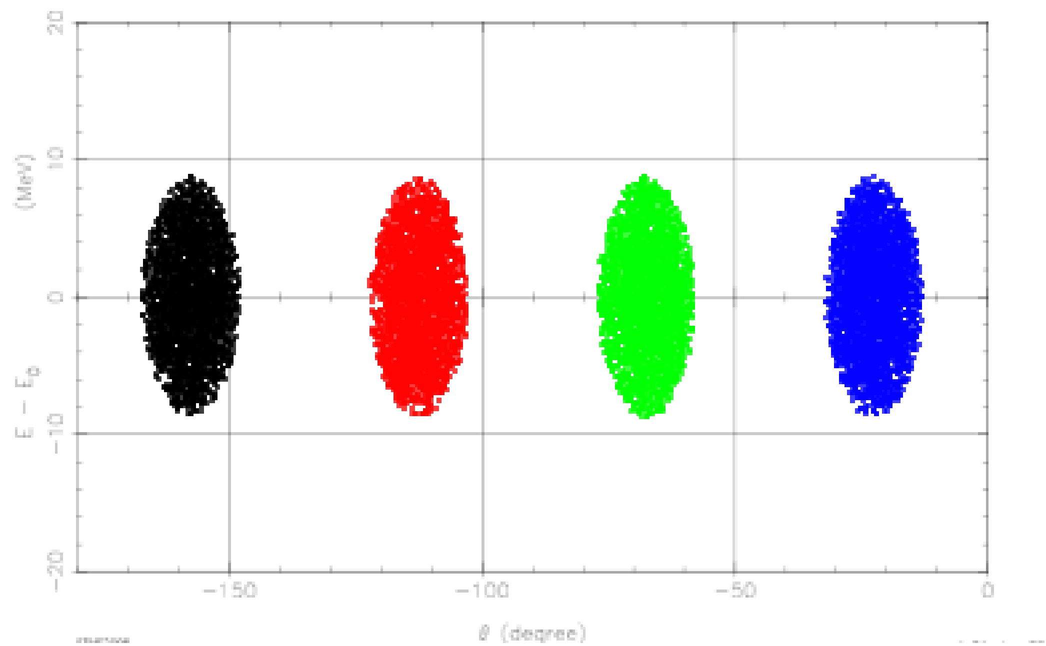
Batch Compression Schemes in the PS
Compression to h_{PS} = 10 and generation of 64 bunches

Animation combining phase space plots from ESME simulations

- Showing half the PS circumference between -180° and 0°
- Voltages adjusted to keep sufficient acceptance (no parasitic bunches in simulation)
- No space charge

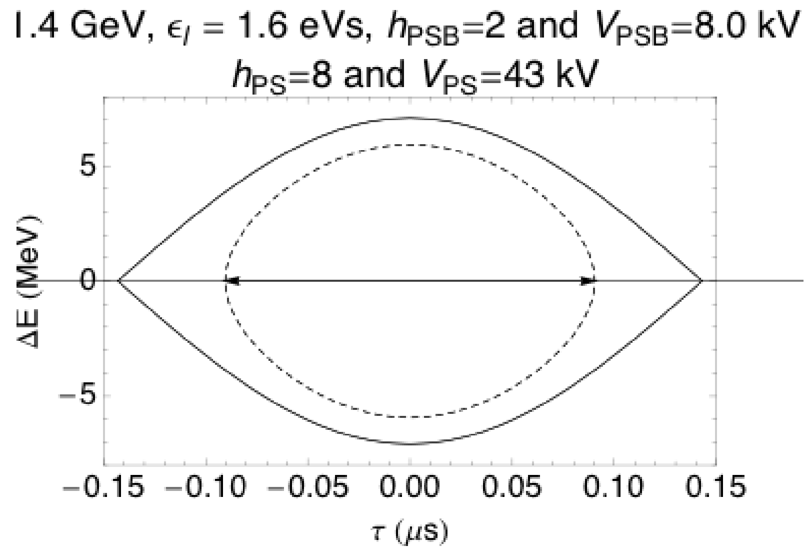
- E_{kin} = 2.5 GeV (working hypothesis for single batch 1.4 GeV injection)



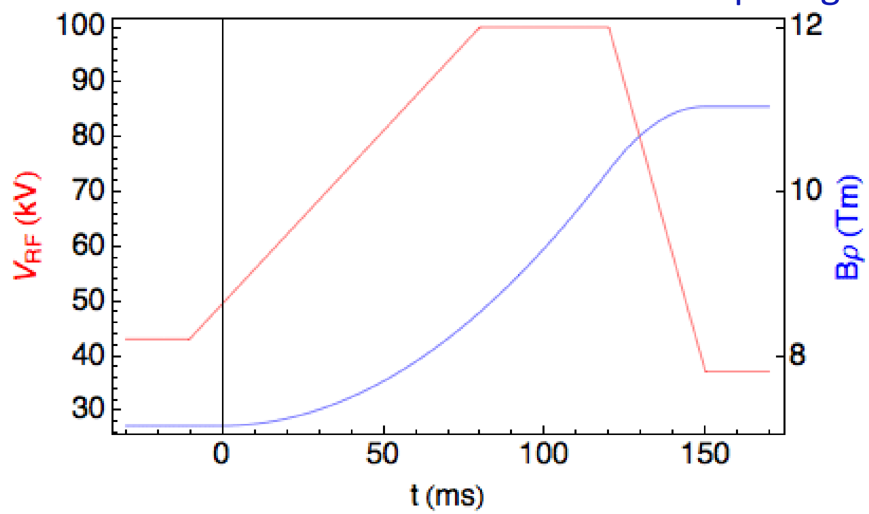


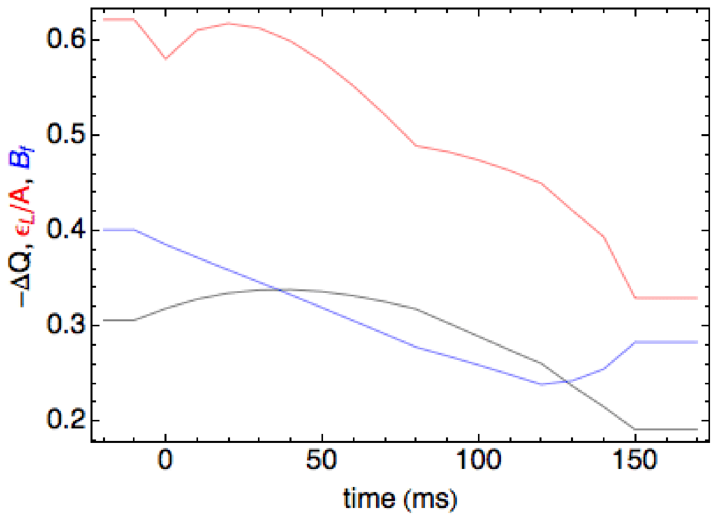
Batch Compression Schemes in the PS
Compression to h_{PS} = 10 and generation of 64 bunches

- Buckets and bunches at injection (neglecting direct space charge)
  - RF voltages in PSB and PS adjusted
    - for longest possible bunches and
    - matching between machines (low RF voltages an issue ?)



- Acceleration in PS from 1.4 GeV to 2.5 GeV plateau
  - Acceleration slowed down to keep longer bunches

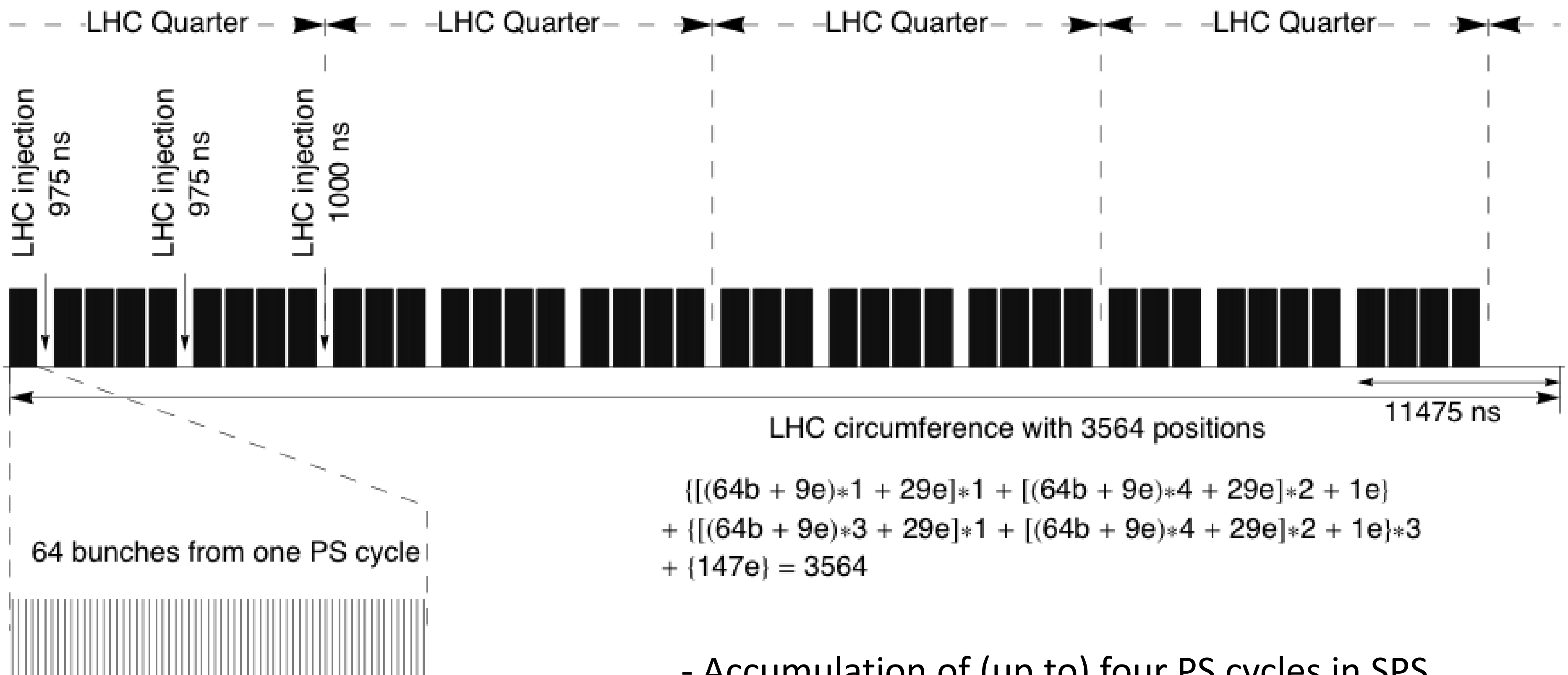




Batch Compression Schemes in the PS

Compression to h_{PS} = 10 and generation of 64 bunches

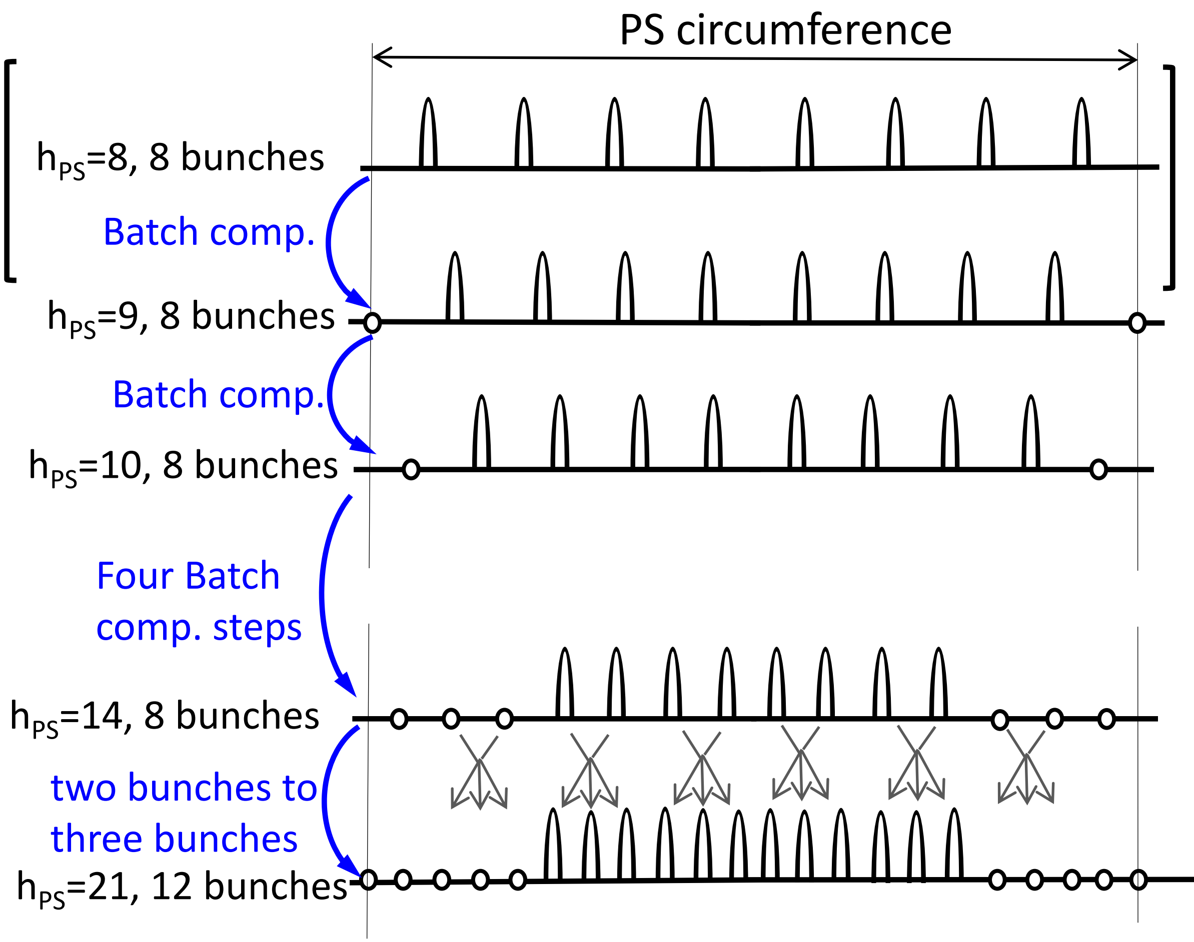
LHC Filling pattern for 64 bunches per PS cycle



- Accumulation of (up to) four PS cycles in SPS
- Number of bunches per LHC reduced by ~4% from 2808 to 2688
- More "PACMAN" bunches

Batch Compression Schemes in the PS
Compression to h_{PS} = 14 and generation of 48 bunches

- Potential brightness increase: 12/6 = 2*
  - Corresponds to PSB upgrade: 1.4 GeV to 2.22 GeV
  - Intensity per bunch for 25 ns trains and 2.5 μm: $3.0\ 10^{11}$
- Estimate of longitudinal parameters at injection for 25 ns trains
  - Every bunch split into 6 LHC bunches with 0.35 eVs
  - 1.2 eVs per injected bunch allows a factor 1.75 blow-up



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Compression to h_{PS} = 14 and generation of 48 bunches

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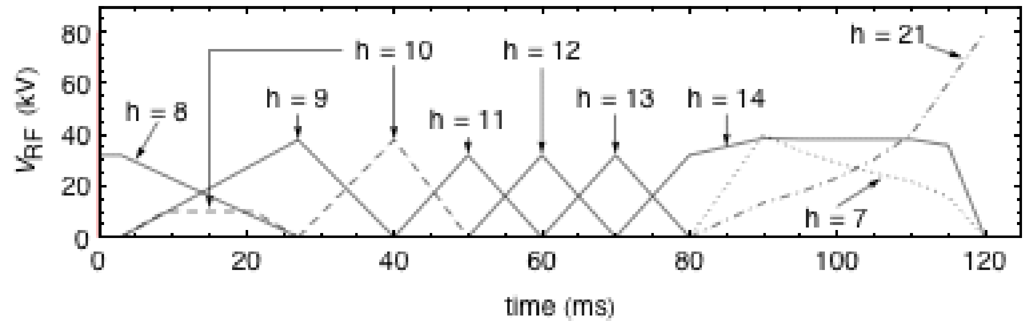

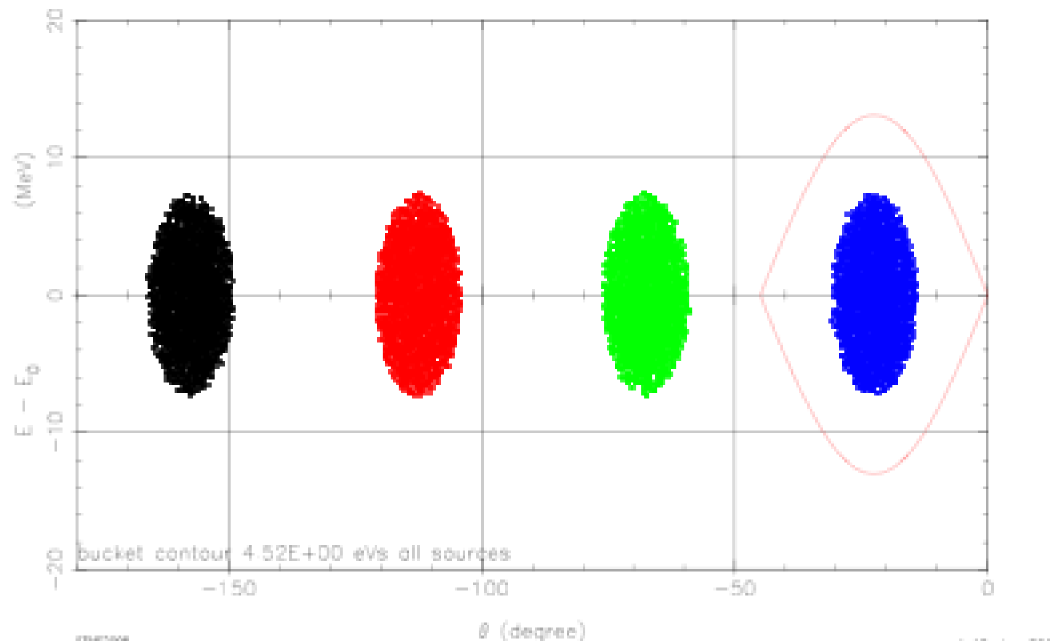

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Compression to h_{PS} = 14 and generation of 48 bunches

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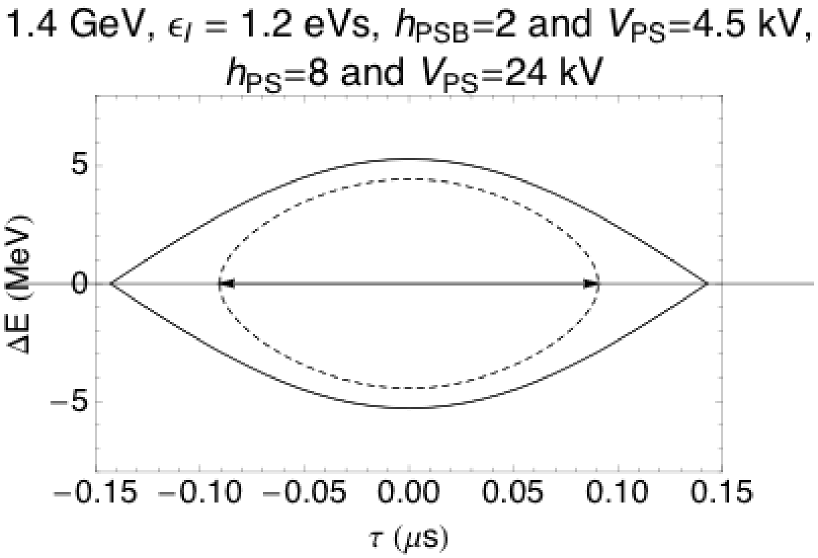

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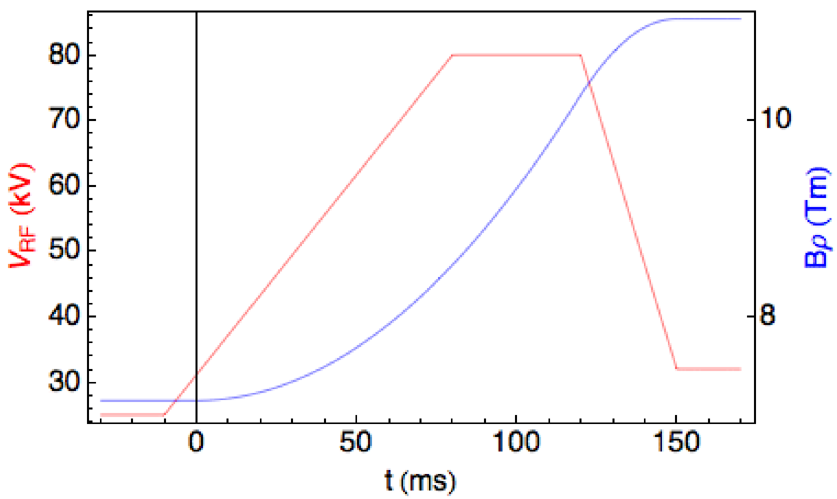
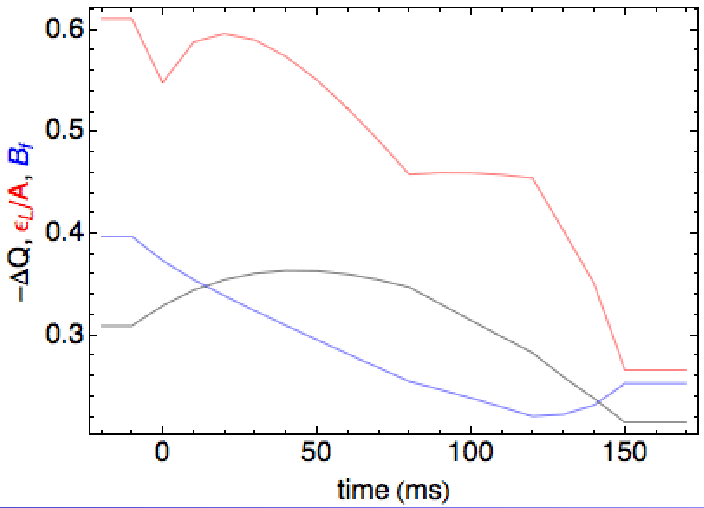
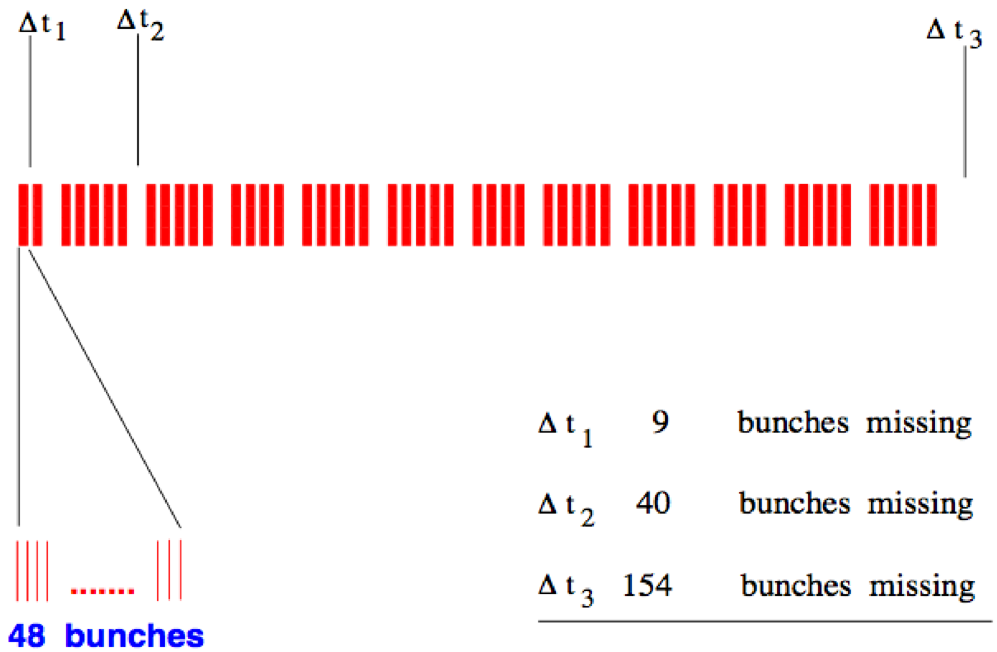




Batch Compression Schemes in the PS
Compression to h_{PS} = 14 and generation of 48 bunches

LHC filling for 48 bunches per PS cycle already worked out in
LHC Project Note 401 (G. Arduini, W. Herr, E. Metral, T. Pieloni)

- Accumulation of (up to) five PS cycles in SPS
- Number of bunches per LHC reduced by ~8% from 2808 to 2592
- More “PACMAN” bunches



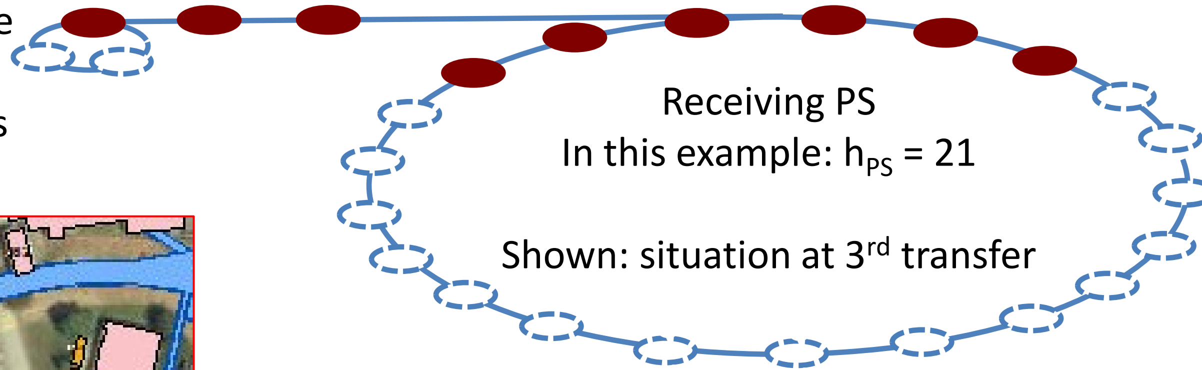
Δt_1	9	bunches missing
Δt_2	40	bunches missing
Δt_3	154	bunches missing

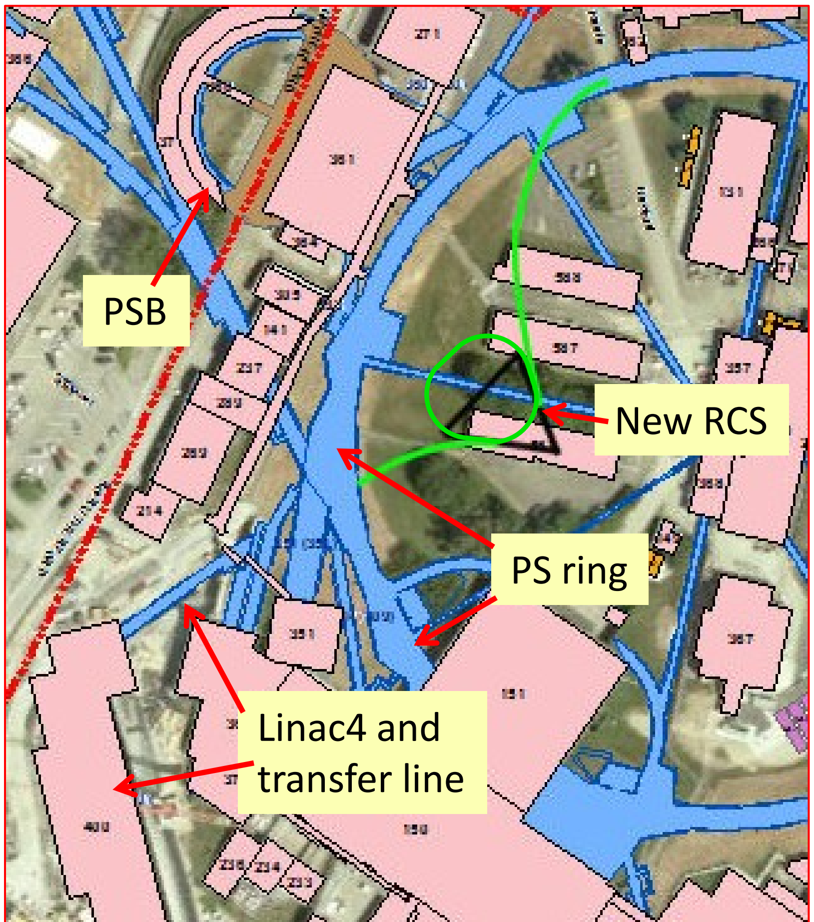
total number of bunches: 2592

$$
\begin{aligned}
& \{[(48b+9e)*2+31e]*1+[(48b+9e)*5+31e]*2\} \\
+ \quad & \{[(48b+9e)*4+31e]*1+[(48b+9e)*5+31e]*2\}*3 \\
+ \quad & \{114e\} \quad = \quad 3564
\end{aligned}
$$

Short RCS as new PS Injector

RCS: 1/7 of PS circumference
In this example: h_{RCS}=3
6 cycles to fill 18 PS buckets





- Short circumference
  - Challenge to reach target kin. energy 2 GeV
  - High brightness for given injection energy (for harmonic number $h_{RCS} > 1$):
    - h_{RCS} = 3 to fill 18 out of h_{PS} = 21 buckets (short kicker gaps) or
    - h_{RCS} = 2 to fill 12 out of h_{PS} = 14 buckets
  - Rep. rate ≈10 Hz (required for Linac4 as well)
- (RCS with circumference 4/21 or 3/14 times the PS might be of interest)

Short RCS as new PS Injector

Magnetic cycles assumed

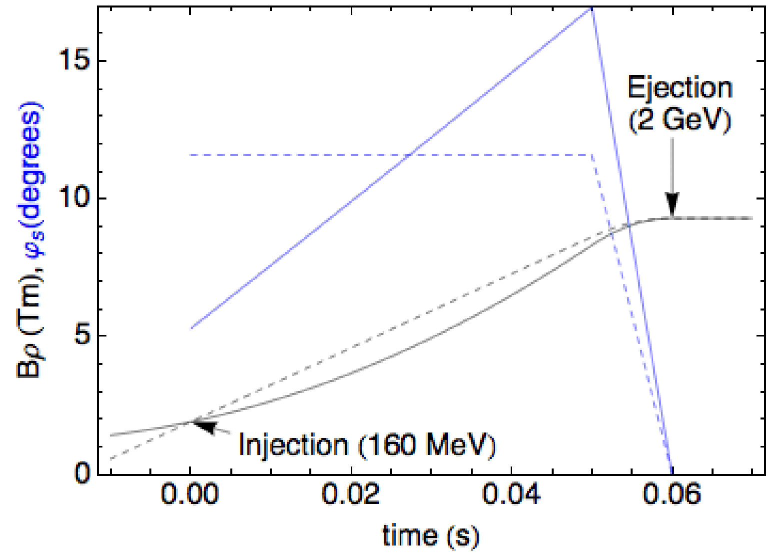
- Solid: Injection with half the average dB/dt, two pieces of parabolas joining at t = 0.05 s
- Dashed: constant dB/dt except rounding during last 10 ms
- Synchronous angles for V_{RF} = 60 kV and circumference 1/7 of the PS

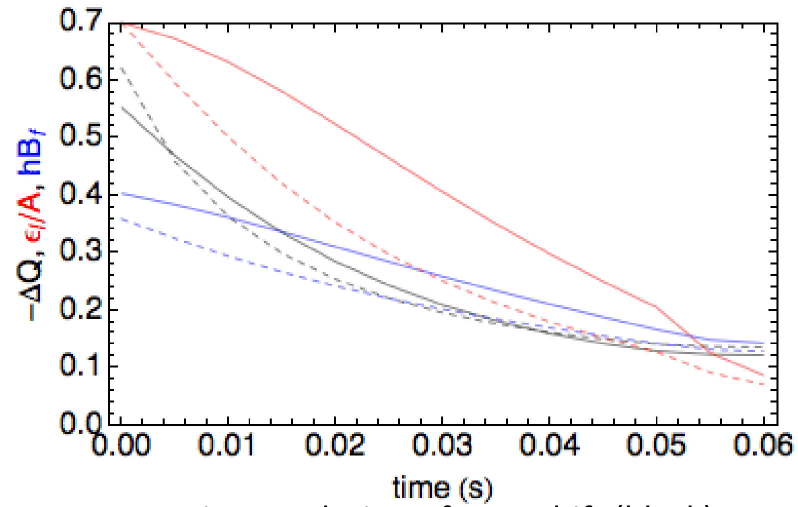
Direct space charge tune shift along ramp

- Long. emittance adjusted to fill 70% of bucket
  - Compatible with maximum long. emittances
- ε^*_{rms} = 2.5 μm and 2.7 10^{11} per LHC 25 ns bunch
- With constant RF voltage along cycle
  - Estimation of height of phase space area occupied by beam used for
  - Estimation of bunching factor and tune shift

- If tune shifts too large for schemes with six transfers
  - Switch to h_{RCS} = 1 and h_{PS} = 14 with 12 transfers

Longitudinal matching at transfer to be studied





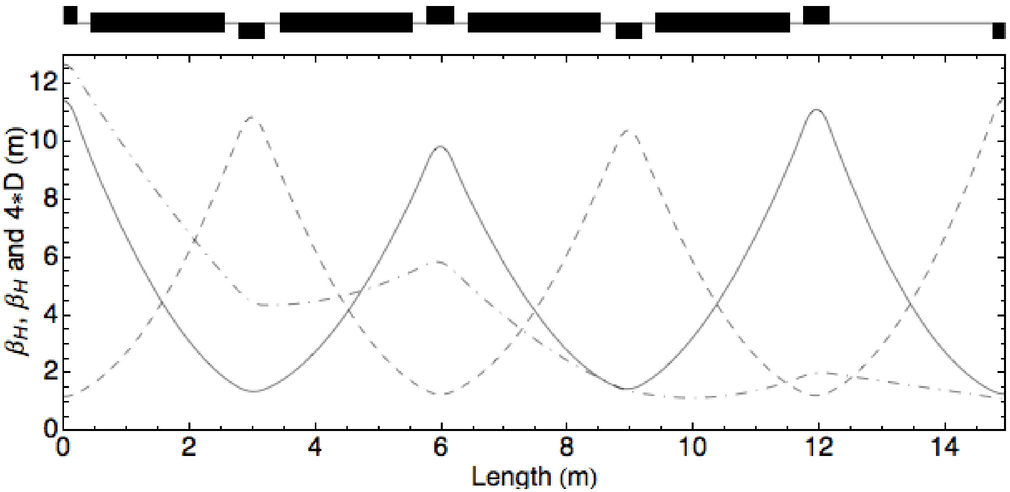
Time evolution of tune shift (black), bunching factor blue and bucket filling (red).

Short RCS as new PS Injector

Studied by M. Benedikt

Envisaged as well
- FODO with 18 cells (5 per arc)
- Triplett for round beams

- First investigations on lattice
  - Periodicity three
    - Straight sections for injection, RF and ejection
  - FODO lattice with 15 cells for efficient focusing
  - ➠ Large bending magnet filling factor (~56%)
  - Tunes around or a bit larger than 4 for suitable transition energy
    - With injection working point of present PSB
    - ➠ up to ~110° phase advance per cell … effect on space charge limit?
- Result
  - Working point of PSB at injection
    - ➠ $\gamma_{transition} = 3.61$
  - 2.1 m long bends
    - ➠ Field at 2 GeV: 1.16 T
  - 0.4 m long quads with $|k| \sim 1.4\ m^{-2}$
    - ➠ quads with ~ 1 T at r = 75 mm
  - 25 cm between quads and bends
  - 2.6 m between quads in straights



Lattice functions for one half-period: solid line denotes β_H, dashed one β_V and dot-dashed one 4*D

- Injection/ejection look feasible … still challenging (preliminary study by B.Goddard)

Short RCS as new PS Injector

Tentative list of main RCS parameter

Energy range	160 MeV to 2 GeV
Circumference	$(200/7)\,\pi$ m ≈ 89.76 m
Repetition rate	~10 Hz
RF voltage	60 kV
Harmonics	h = 2 or 3
Frequency range	3.48 MHz (h=2 at injection) to 9.5 MHz (h=3 at ejection)
Beam parameters for LHC (for lower emittances scale down intensity accordingly)	Intensity: up to $12 \times 2.7\ 10^{11}$ protons/cycle Transv. emittance: $\varepsilon^{*}_{rms} \approx 2.5\ \mu$m Long. emittance: $\varepsilon_l < 12 \times 0.27$ eVs (determined by acceptance for most cases)
Lattice	FODO with 15 cells and 3 periods, 4 cells in arc, straight with one cell
Tunes	$4 < Q_{H,V} < 5$
Relativistic gamma at transition	~4
Bending magnet filling factor	56 %
Maximum magnetic field	1.16 T

Summary

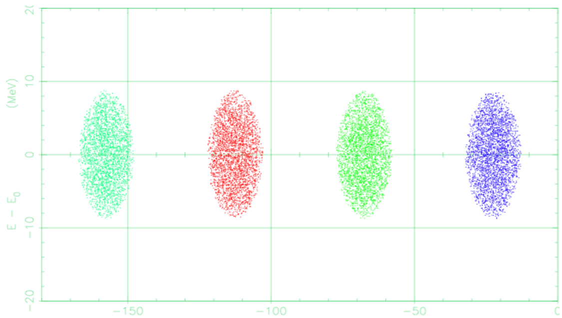
- Batch compression schemes to increase brightness in PS
  - Scheme yielding 64 bunches per PS batch
    - Brightness increase compared to present situation: 1.5
    - Reasonable complexity of RF gymnastics
  - Scheme yielding 48 bunches per PS batch
    - Brightness increase compared to present situation: 2
    - Complex RF gymnastics with many batch compression steps
  - RF gymnastics to be refined (time for cavity tuning, of RF voltage functions …)
  - Implication (slow initial acceleration, time for gymnastics) on PS cycle?
  - Tests (with double batch transfer) possible without expensive hardware upgrades …
    - ... but significant manpower and efforts from the PS RF team and MD time required!
  - Potential to combine PSB energy upgrade with batch compression
    - Requires double batch PSB to PS transfer

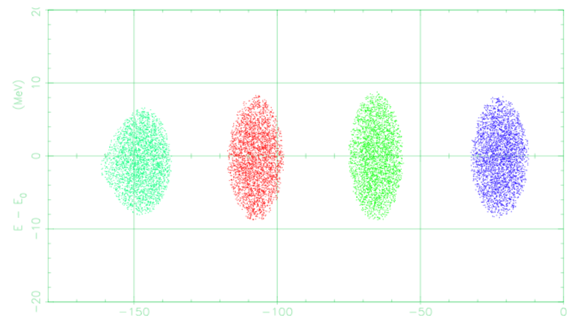
Based on delicate and complex RF gymnastics ... especially with intensities foreseen

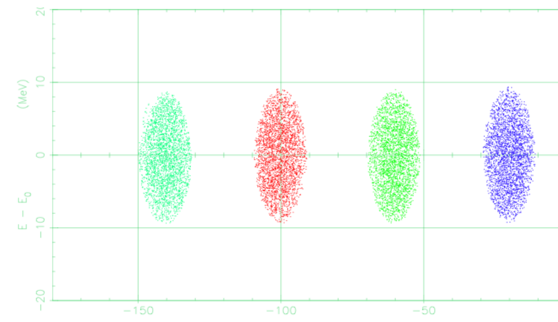
Potential interest now with Linac2

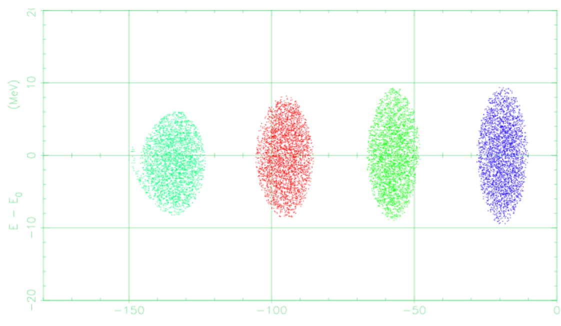
- Rapid Cycling Synchrotron as new PS injector
  - Very first estimates only possible within time available
    - Some parameters (e.g. bending filling factor and magnetic field) challenging ….
    - … but no showstopper identified for the moment, Linac4 has to cycle faster as well
  - Feasibility can only be answered after a more thorough study

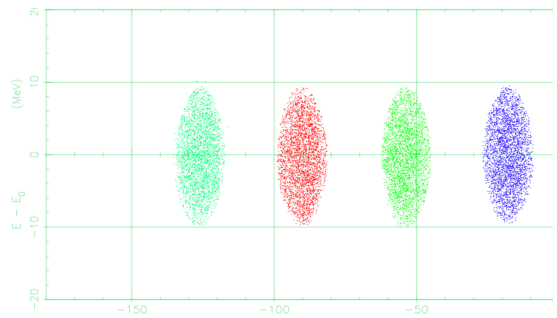
Batch Compression Schemes in the PS
Compression to h_{PS} = 10 and generation of 64 bunches

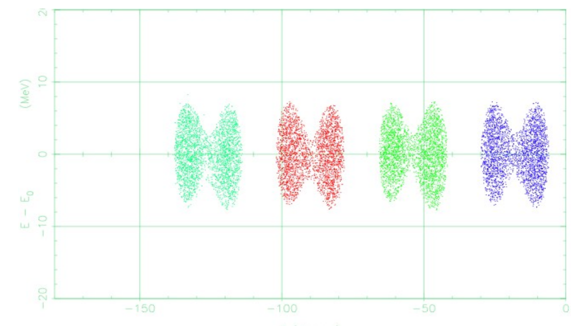

t = 3 ms (start)

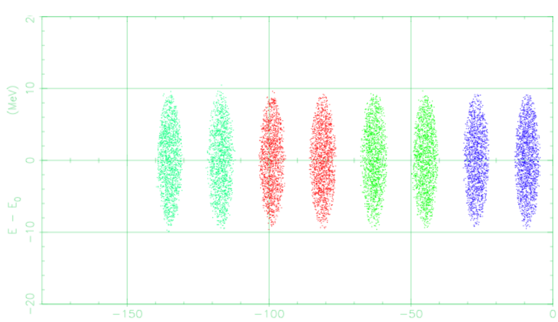

t = 13 ms (during 1st compression step)

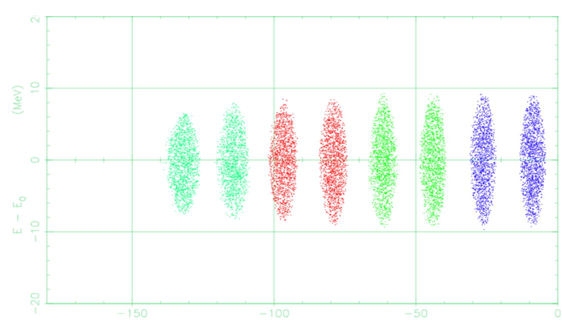

t = 27 ms (pure h = 9)

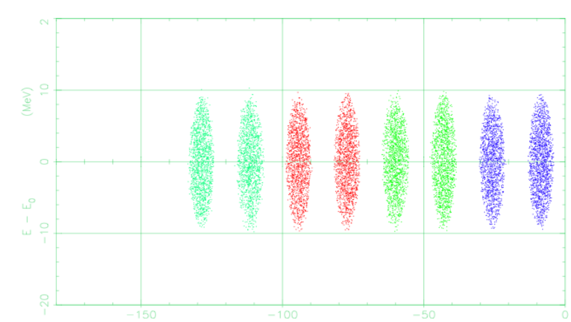

t = 33 ms (during 2nd compression step)


t = 40 ms (pure h=10)


t = 50 ms (splitting)


t = 60 ms (pure h=20)


t = 65 ms (during last compression step)


t = 80 ms (pure h = 21)