Review on PS Booster with Linac4

Booster Beam Dynamics

Christian Carli

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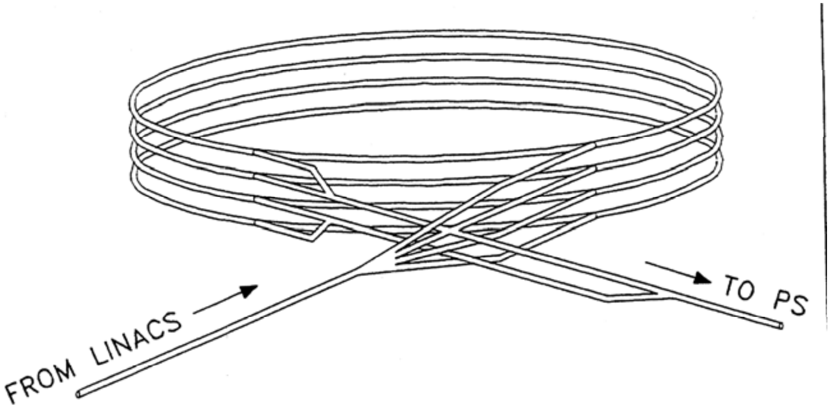
On behalf of the team working on and contributing to the study:

- M. Aiba did most ORBIT simulations (Booster modelling …. injection)
- R. Garoby: longitudinal painting scheme …..
- B. Goddard, W. Weterings and team: injection hardware, help implementing it in ORBIT
- M. Martini carried out ACCSIM simulations
- M. Chanel: experience on PS Booster operation and 160 MeV measurements
- S. Cousinau and her colleagues at SNS for help and advice on ORBIT
- F. Ostiguy for advice and help with ESME and explanation on FNAL H^- injection
- A. Findlay, S. Hancock, K. Hanke, B. Mikulec, F. Gerigk …..

Overview of the presentation

- Introduction
  - CERN PS Booster (PSB) Overview
  - Motivation for Linac4 and PSB Beam Dynamics Studies
- Active longitudinal Painting
- Issues Related to the new H^- Charge Exchange Injection
  - Lattice Perturbations by the Injection Chicane
  - Conceptual Aspects for the Injection Layout
  - Scenario proposed (Layout, Machine Acceptance)
- Simulations of Beam Dynamics with strong direct Space Charge Forces
- Activities and Plans for the working Group on PSB Beam Dynamics with Linac4
- Status and Questions

Introduction – CERN PS Booster (PSB) Overview

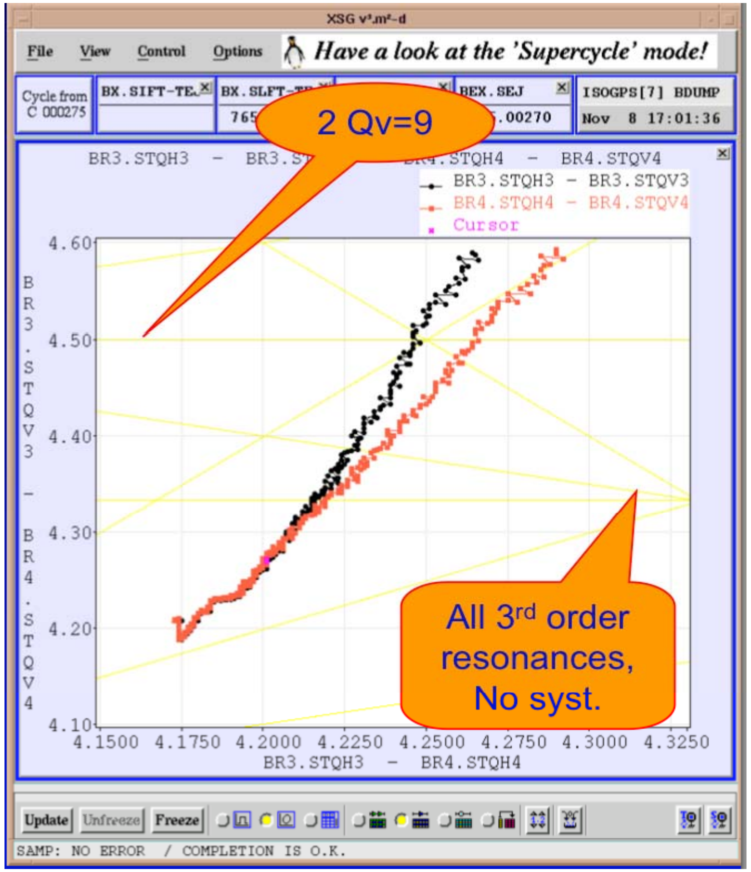


Sketch of the PS Booster with:
- Distribution of Linac beam into 4 rings
- Recombination prior to transfer

- Recapitulation of the present Booster with Linac2:
  - Constructed in the 70ies to improve the performance (intensity) of the PS
  - Four superimposed rings (chosen instead of fast cycling synchrotron or 200 MeV Linac)
  - 16 cells with triplet focusing, phase advance >90^o per period
  - Large acceptances: 180 π μm and 120 π μm in the horizontal and vertical plane, respectively
  - Multiturn injection with betatron stacking and septum at 50 MeV
  - Acceleration to 1400 MeV (was 800 MeV at the beginning)

Introduction – CERN PS Booster (PSB) Overview

- Mandatory for high Intensity and Brightness
  - Double harmonic RF (now: h=1 and h=2),
  - Resonance compensation,
  - Dynamic working point …
  - Maximum direct space charge tune shifts larger than 0.5 in the vertical plane
- Intensities above 10^{13} protons per ring (more then four times design) obtained
- Versatile machine - many different beams with different characteristics



Dynamic Working point with lower vertical tune – no syst. 3rd order resonance (taken from a presentation by M. Chanel)

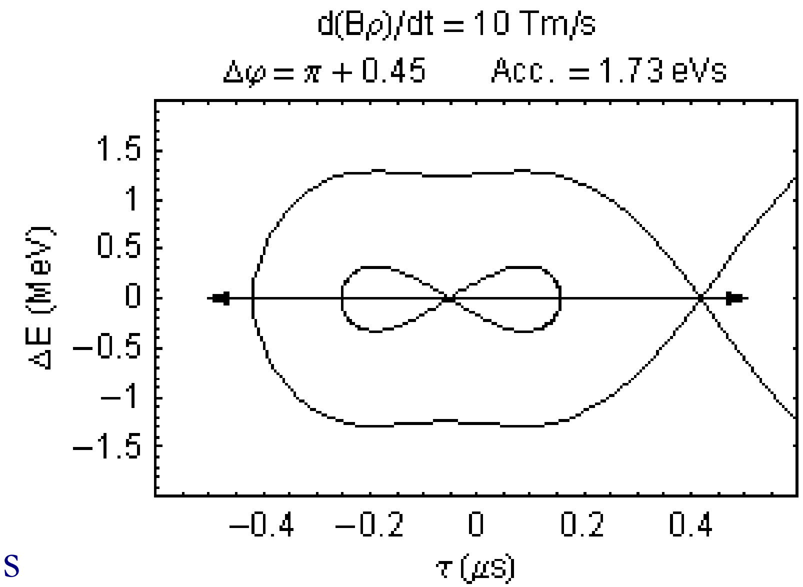
- PSB to PS Transfer Energy:
  - Increased (in two steps) from 800 MeV to 1400 MeV to reduce direct space charge effects in the PS
  - Direct Space Charge at PSB Injection a Bottleneck

Introduction –
Motivation for Linac4 and PSB Beam Dynamics Studies

- Rationale for Linac4:
  - PS Booster limited by direct space charge effects, quantified by direct space charge tune shift ΔQ, at injection energy
  - Increase injection energy such that the brightness can doubled (double intensity within unchanged normalized emittances) without changing ΔQ
  - Raise injection energy from 50 MeV with Linac2 to 160 MeV with Linac4
- Convert to H^- charge exchange injection
  - Reach the Phase Space Density expected in the PSB
  - Allows - with a Linac4 Beam chopper - for longitudinal Painting
  - New injection hardware for increased injection energy and charge exchange injection
- Aim of PSB Beam Dynamics with Linac4 studies
  - Answer the question: Is above argument the whole story?
    (e.g. the Beam will stay a bit longer with large ΔQ in the PSB)
  - Thorough understanding of the implications of Linac4 on the PSB
  - Make sure that PSB performance expected with Linac4 is reached fast:
    - Anticipate possible additional limitations & difficulties and devise for cures
    - Ensure integration of PSB with Linac4 into the complex (versatility ….)
  - No direct responsibility for hardware construction, but findings expected to have significant impact on hardware (upgrades, instrumentation ..) and PSB performance with Linac4
- Next bottleneck around the corner: PS and SPS at low energy

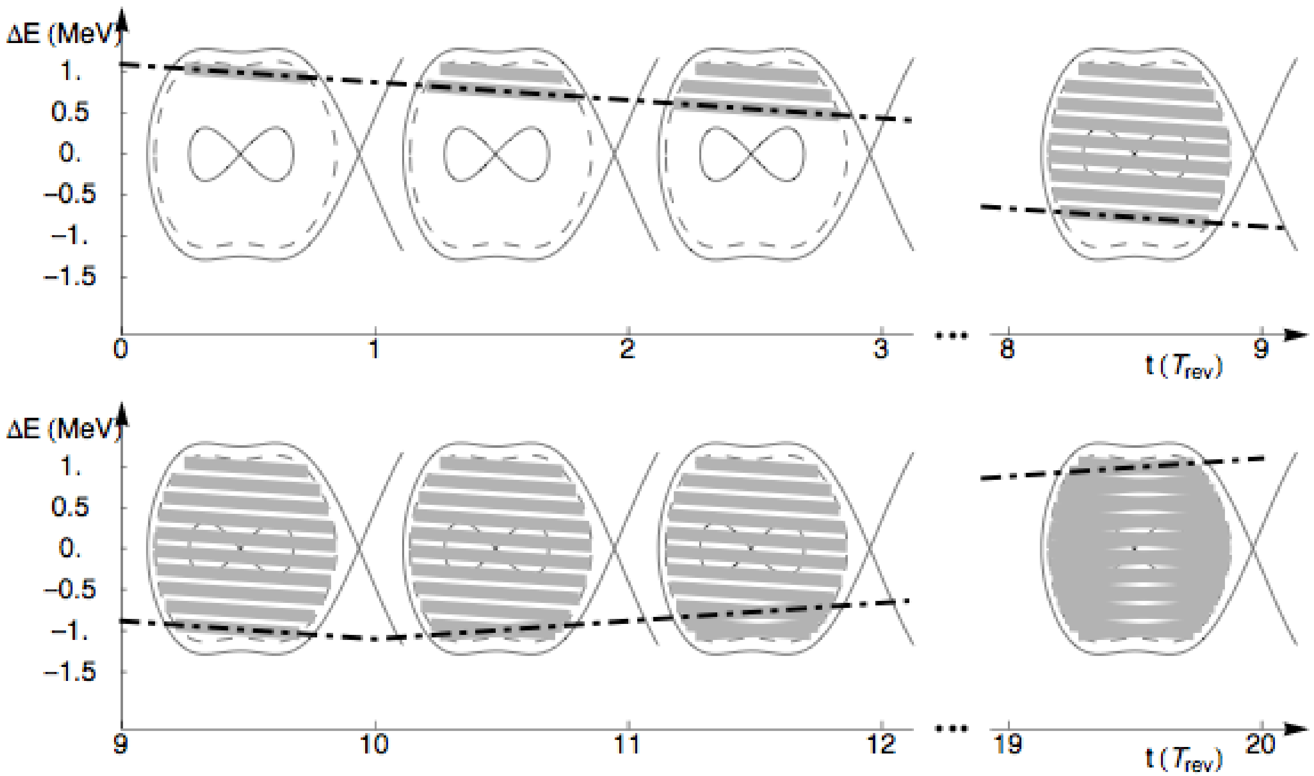
Active longitudinal Painting

- With Linac4: similar RF system than at present
  - Double harmonic
    - fundamental h=1 and h=2 systems to flatten bunches
    - reduces maximum tune shifts



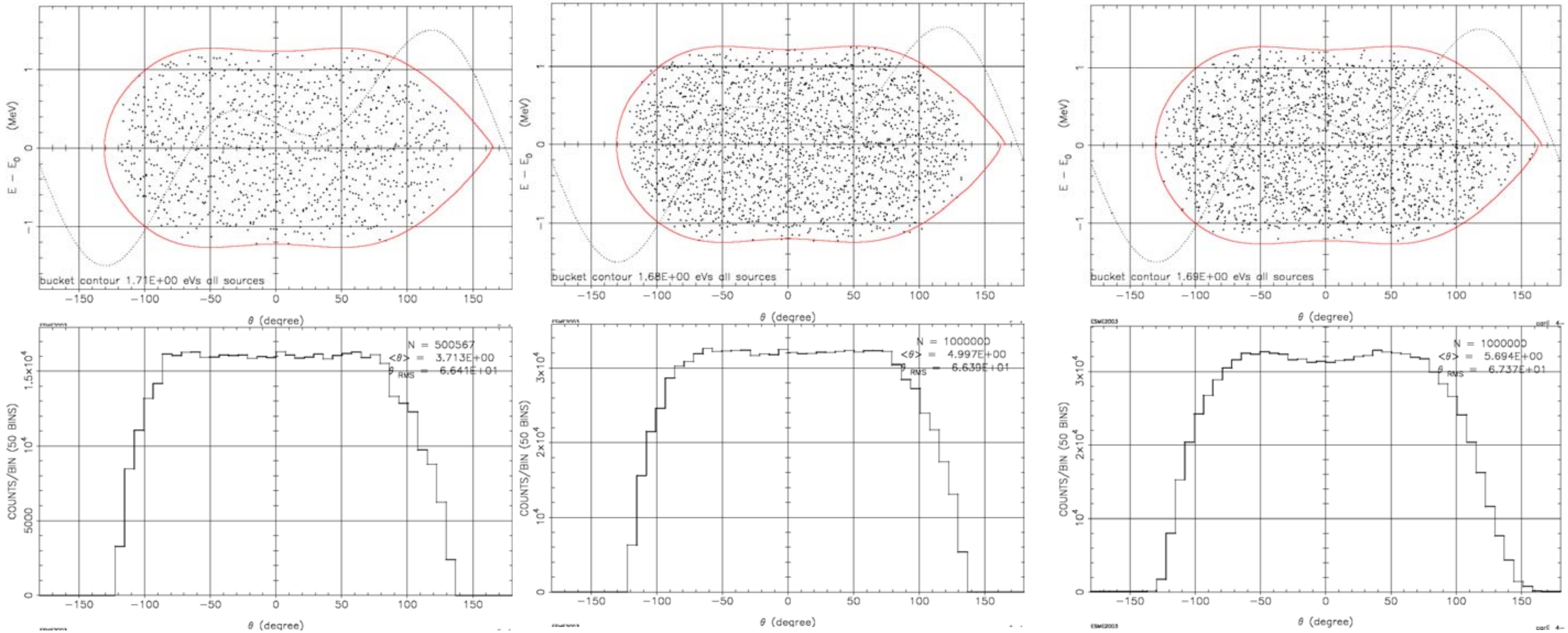
  - Injection with $d(B\rho)/dt = 10$ Tm/s (no need for injection with small ramp rate with painting any more)
  - Little (but not negligible) motion in longitudinal phase space.
  - No way for painting from synchrotron motion (large harmonic numbers and RF voltages ruled out)
  - ➢ Need for active painting (aim: fill bucket homogeneously) and energy modulation

Active longitudinal Painting



- Principle:
  - Triangular energy modulation (slow, ~20 turns for LHC)
  - Beam on/off if mean energy inside a contur ~80% of acceptance
  - Nominal LHC: intensity with 41mA (!!!) after 20 turns
  - High intensity: several and/or longer modulation periods
- Potential limitations: Linac4 jitter, debunching of Linac4 structure in Booster
- Note that D ~ 1.4 m at the PSB injection
- Ideas on implementation: see talk on "RF Aspects …"

Active longitudinal Painting

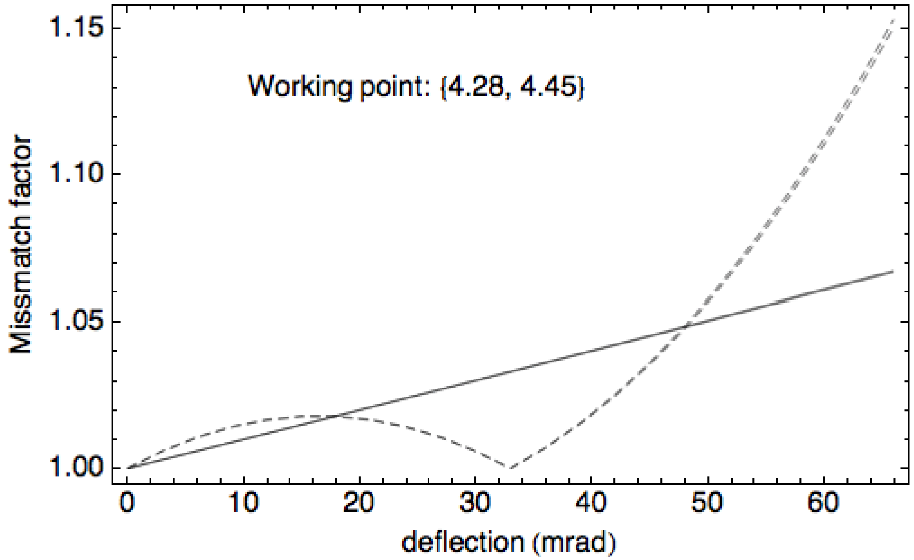


After 10 turns after 20 turns (completed injection) after~3000 turns

- Simulation with ESME for nominal LHC beam:
  - Energy modulation 1.1 MeV, plus rms spread 120 keV
  - About 98 % of particles at the and buching factor ~0.60.
- High intensity (reduced bucket hight due to direct space charge):
  - Similar results with reduced E modulation

Issues Related to the new H- Injection – Lattice Perturbations by the Injection Chicane

- Problem (thanks to F. Ostiguy for drawing our attention on limitations at FNAL)
  - Chicane (to merge injected with circulating beam) dipoles add focusing initially envisaged: rectangular bends without gradients
  - Lattice perturbation (strong in vertical plane … tune close to resonance)
  - Long chicane dipoles and small deflections to reduce perturbations
- "Passive" compensation (M. Aiba, TE/ABT team working on hardware)
  - Replacing rectangular bends by sector bends or adding gradients brings (part of) the perturbation into horizontal plane
  - Less horizontal beta-beating, because tune is further away from half-integer resonance
  - Pole-face windings on chicane magnets for "active" compensation?

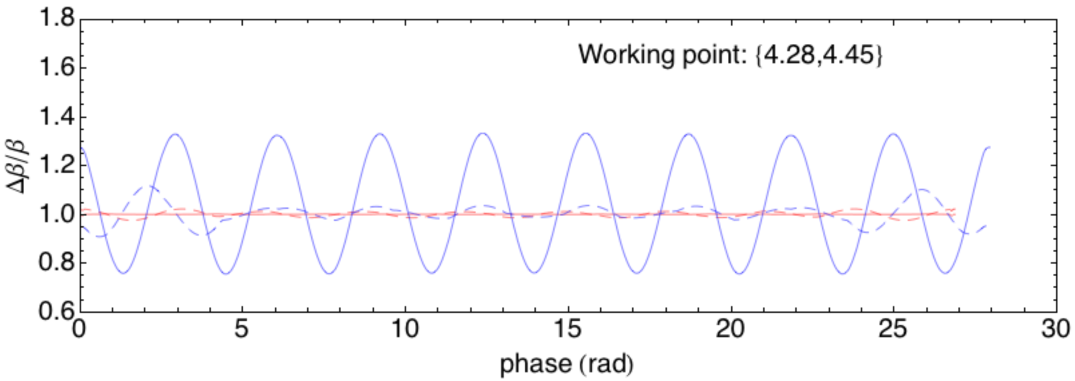


Example: long chicane dipoles & small deflections
max. deflection of chicane dipoles: 66 mrad,
pole face rotations: 33 mrad

Issues Related to the new H- Injection – Lattice Perturbations by the Injection Chicane

- "Active" compensation with trims on appropriate QDE quads:
  - Proposal (M. Aiba, B. Goddard ..) for additional quads ruled out initially: complicated scheme with similar β-function in both planes for quads in straights
  - Trims on QDE quadrupoles are appropriate (chicane made of rectangular bends):
    - Large (β-function and) compensation in vertical plane with little (β-function and) perturbation in the horizontal plane
    - In practice: trims on appropriate "Q-strips" (additional windings of PSB quads)
    - Appropriate quads for "lower vertical tune: QDE03 and QDE14

β-beating with (dashed) and without (solid) compensation
Blue: vertical; red: horizontal



- Compensation during (no compromise) whole chicane fall
- Preliminary discussion on Power Converters: feasible provided chicane fall time is not too short (at least a few ms)

Issues Related to the new H- Injection – Conceptual Aspects for the Injection

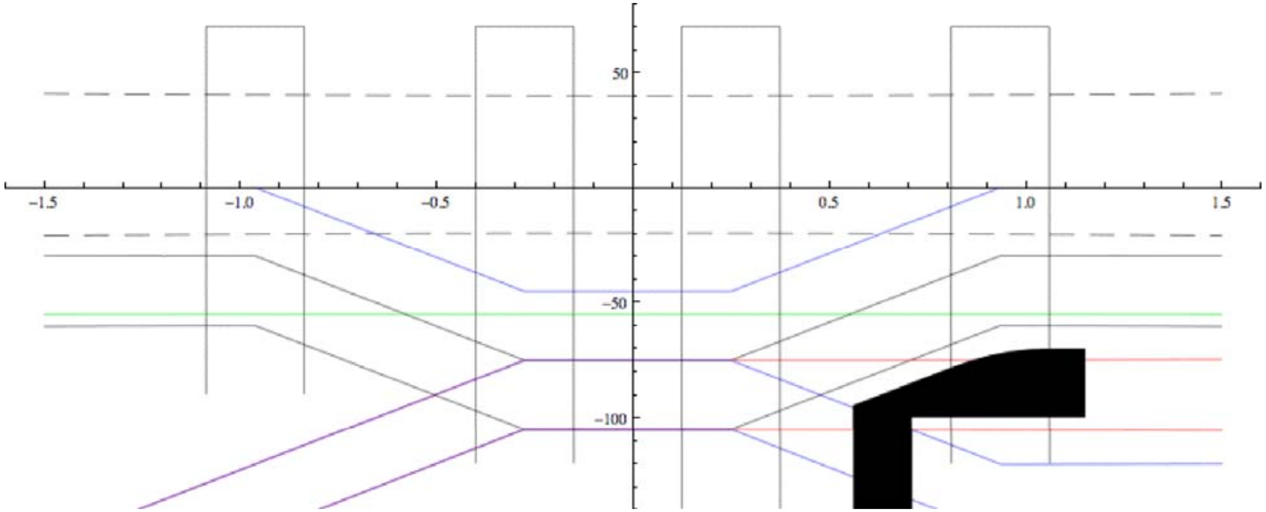
- Dynamic working point and vertical tune at injection:
  - At present: highest intensity with vertical tune at injection above half-integer resonance (but below for LHC type beams)
  - With Linac4 always below half-integer resonance:
    - Double brightness for LHC,
    - Less than twice the intensity for high intensity (less losses, limited by machines further downstream as well)
- Dispersion matching:
  - Large energy modulation for longitudinal painting and dispersion of PSB
    - If beam arrives from Linac4 with D=0 m (dispersion mismatch): correlation of transverse emittance and position in longitudinal phase space
    - Should beam arrive with D matched to the PSB lattice (see chapter on simulations)
- Acceptance with Linac4
  - At present: Large beams close to limit of ejection channel acceptance (losses)
  - With Linac4: aim for same maximum emittances at ejection
  - ➢ Smaller physical emittances at injection -> reduce machine acceptance
  - ➢ For acceptances: A_H=130 μm, A_V=60 μm and $A_{\Delta p/p}$=±2.2 10^{-3}:
  - ➢ Half-apertures in long straights: horizontal ±33 mm and vertical ±18 mm
  - ➢ Can one take profit of a localized aperture to concentrate losses?

Issues Related to the new H- Injection – Conceptual Aspects for the Injection

- Layout of the injection region (mainly by TE/BT team working on hardware)
  - Superposition of two closed orbit bumps:
    - Chicane to merge incoming H^- beam with circulating protons
    - Injection painting bump: horizontal painting and removes beam from foil
  - Options (with different conceptual approaches)
    - Small injection bump and "high" chicane (baseline):
      - No problems with apertures
      - Chicane is used as well to remove circulating beam from foil
    - Large injection bump and small height of chicane (ABP proposal):
      - Foil outside of machine acceptance after fall of chicane
      - Aperture in bends within injection painting bump critical
  - Plans for the near future:
    - Evaluation of the two options by simulation with failures (e.g. painting triggered bump too early and injection with large betatron amplitudes)
    - Fix layout (and specify maximum chicane fall time)

Issues Related to the new H- Injection – Scenario proposed (foil outside acceptance without painting bump)

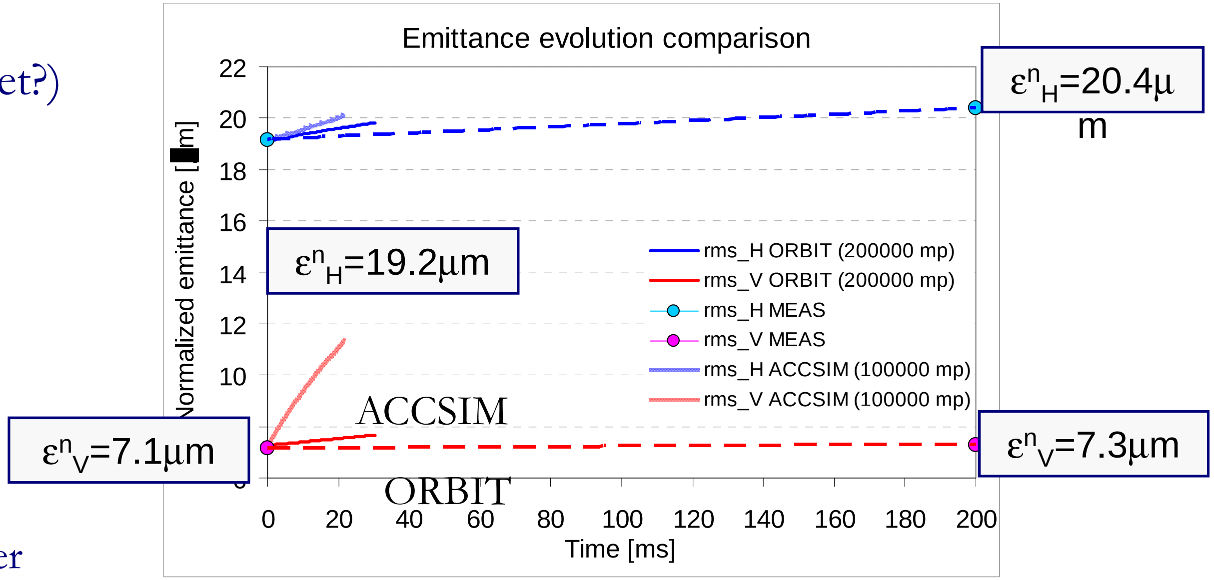
- Limiting aperture ("BeamScope" like) in straight ~2π from foil (5L1)
  - Aperture displaced towards inside of PSB -23 mm to +43 mm to save aperture for the injected beam -> "average" momentum (for large beams) $\Delta p_{av}/p$ = -10mm/D
- Height of painting bump:
  - Distance chicane to inner edge of foil: 33 mm + 7mm = 40 mm
  - Distance edge of foil to incoming beam ($\Delta p_{av}/p$) : $3*(2\beta\ \varepsilon_{rms})^{1/2} + D\ \Delta p_{paint}/p$ ~ 15 mm
  - Height of the injection painting bump: 55 mm (instead of 35 mm proposed by BT)
  - Problem: tight for aperture (taken by painting bump)



- Make use of acceptance reduction to implement rough collimation
  - Thin aperture defining acceptance (at beginning) in straight section
  - Thicker absorber behind in same straight section and/or in straights further downstream
  - First step: look into feasibility

Simulations of Beam Dynamics with strong direct Space Charge Forces

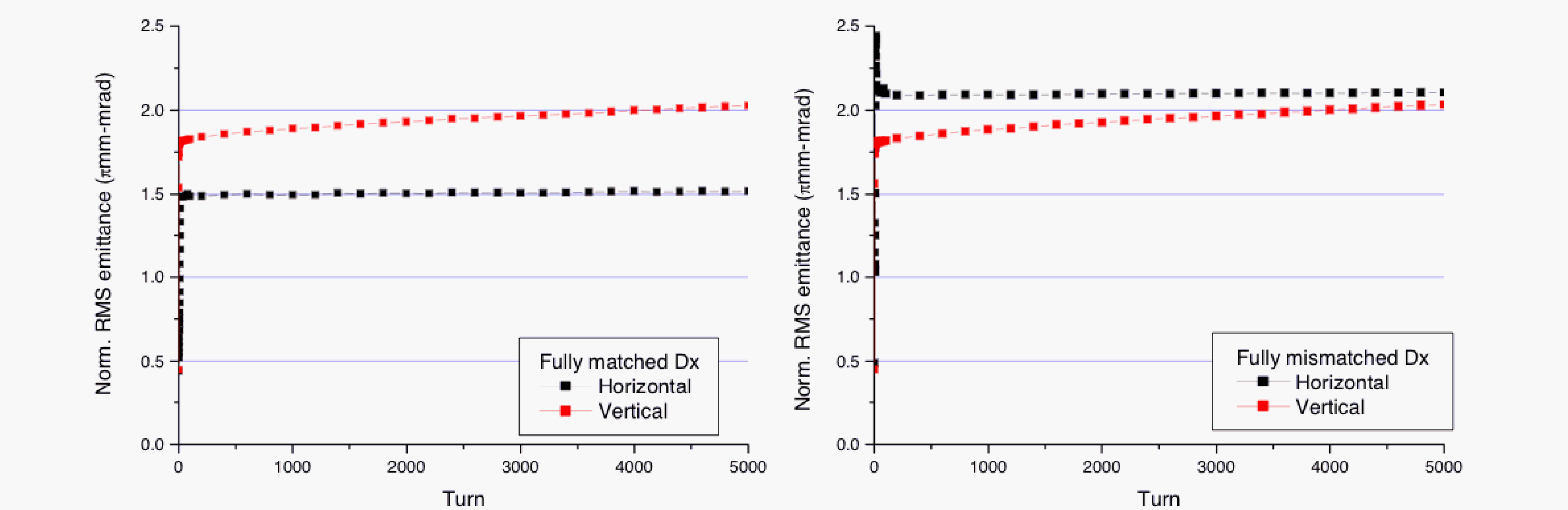
- Assessment of slow blow-up by Simulations feasible?:
  - Benchmark comparing measurements (by M. Chanel) with simulations (by M. Aiba and M. Martini) and between ACCSIM and ORBIT (M. Aiba and M. Martini)
  - For the moment, no satisfactory agreement (yet?)
  - Example:
    - 2nd harmonic RF to shorten bunches to increase tune shift
    - ACCSIM largely overestimates blow-up
    - ORBIT overestimates blow-up as well
    - Dependance on number of macro-part's
    - Numerical artefacts?



  - Successful benchmark is prerequisite to apply simulations for blow-up and loss estimates

Simulations of Beam Dynamics with strong direct Space Charge Forces

- Impact of injection matching and painting on PSB performance
  - Filamentation of structure due to injection dispersion mismatch?
  - Investigated by M. Aiba with input from B. Goddard – longitudinal and transverse painting of an LHC type injected over 20 turns

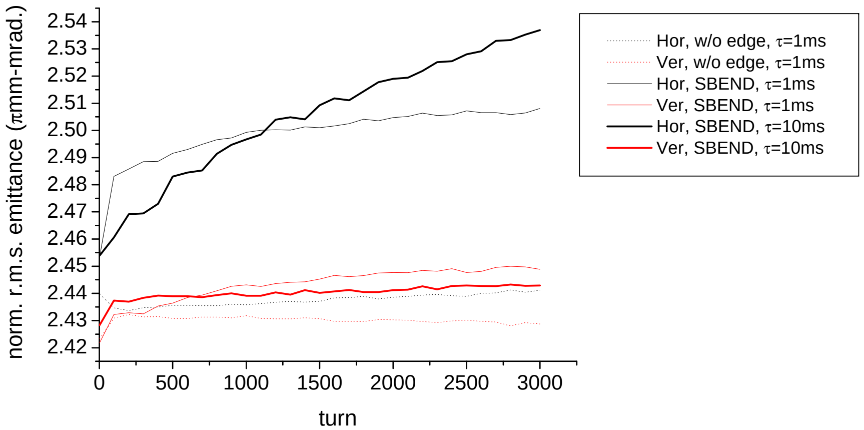


Evolution of rms emittances after injection - blow-up (extrapolation ?) may be too large (slightly larger relative blow-up for 99% and 100% emittances)

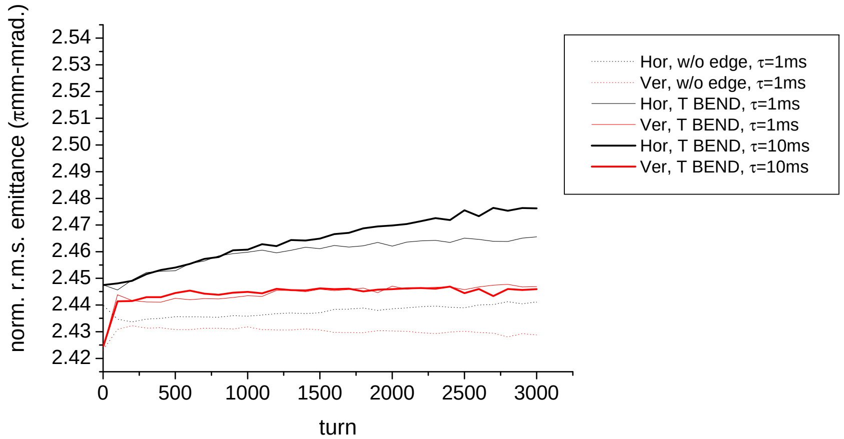
  - No significant difference with and without dispersion mismatch
  - To do: Impact (minor ?) of transverse matching and painting on performance?
- Simulation on impact on and of the injection foil by BT team and M. Aiba

Simulations of Beam Dynamics with strong direct Space Charge Forces

- Evolution of beam parameters during fall of chicane with lattice perturbations and passive compensations and different fall times (simulations by M. Aiba)
  - “Passive” compensation (see above) by pole-face rotation of chicane magnets yield
  - Simulations with ORBIT and additional routine for time dependant focusing of chicane, but no synchrotron oscillations
  - Simulations indicate significant reduction of blow-up



Chicane: L_{BS} = 0.25 m and sector bends



Chicane: L_{BS} = 0.25 m and “tapered” bends

- Lattice perturbation and “active” (by trims on QDE’s) compensation
  - Injection painting, “static chicane and compensation” and with synchrotron motion
  - Similar results (compensation reduces blow-up)

Activities and Plans for the working Group on "PSB Beam Dynamics with Linac4"

- Proposed longitudinal painting proposed and follow-up (implementation, see talk on "RF aspects and possible limitations")
- Beam dynamics with strong direct space charge forces
  - Benchmark to which extent simulation are appropriate tools
  - Apply simulations: filamentation of structure from injection, losses slow blow-up … ?)
- Beam dynamics issues related to the new H^- charge exchange injection (with BT team)
- Integration into the CERN Complex (see talk on "Operational Scenarios …"):
  - Generation of all (also low intensity without painting) beams to be provided, minimization of losses and activation
  - Transfer of LHC type beams between PSB and PS
- Check limitations of present Booster hardware:
  - Instabilities (existing damper with higher intensities)
  - (Beam loading problems of h=2 cavities for h=1 beams … limitations ISOLDE beams ?)
- Beam Losses, Activation ("normal" losses, failure scenarios …):
  - Losses at Injection (Line and Ring) in collaboration with or by injection hardware team ?
  - Feasibility of rough Collimation System (if feasible, resources need to be requested and allocated)

Summary, Status and Questions

- Linac4 aims at increasing the brilliance out of the PSB by about a factor 2.
- Beam dynamics studies aim:
  - Thorough understanding of implications of Linac4 on PSB
  - Anticipating problems to implement measures ensuring fast and efficient (i) restart of the PSB with Linac4 (ii) performance increase to expected levels
- Status
  - Progress on many topics during the last year, but work on some topics still in starting phase
  - Present priority on studies with possible impact on hardware (e.g. finalization of injection)
- Questions to the review board:
  - Validation of proposed longitudinal painting
  - Advice on finalization of injection layout
  - Validation of proposed reduction of the machine acceptance
  - Advice on simulations with strong direct space charge effects