Space charge effects and machine resonances
CERN Injectors for LHC (LIU project)

Alexander Molodozhenstev (KEK)
October 29, 2012
CONTENT

→ CURRENT status of the group activity for the period March – October 2012

- Motivation for this activity
- Plans and Current status of the group activity
  → Computational tools and hardware …
  → MDs and benchmarking activity …
  → Status of the simulation activity …
- Next mile-stones in the group activity
CERN Space charge Group (ABP-ICE)

Group manager: Frank Schmidt

External expert: Alexander Molodozhnetsev (KEK)

PS Booster: Vincenzo Forte, Michel Martini, Elena Benedetto, Nicolas Mounet, Christian Carli

PS: Raymond Wasef, Cedric Hernalsteens

SPS: Hannes Batisik

‘RCS’ design: Miriam Fitterer

Thanks everybody for the contributions to this presentation.
Motivations … LHC 25 nsec

2011: ~ 1.1e11 with 2.8μm for 25nsec has been extracted from SPS

Post LS2 (2019): \( \times 2.4 \) times in brightness for 25nsec

Alexander Molodozhentsev (KEK)
Motivations ... key-points

- LINAC2 (p+ 50MeV) → LINAC4 (h- 160MeV)
- PS Booster \(\rightarrow W_{\text{inj}} = 160\text{ MeV}\)
  ... very confident to run with \(\Delta Q_y \approx -0.3\) (and reasonable hope for \(\Delta Q_y \approx -0.36\))
- PS \(\rightarrow W_{\text{inj}} = 2\text{ GeV}\)
  ... very confident to run with \(\Delta Q_y \approx -0.26\) (with reasonable hope for \(\Delta Q_y \approx -0.30\) with 180nsec long bunches)
- SPS (Q20 lattice)
  ... present assumption is to run with \(\Delta Q_y \approx -0.15\)
  ... need to increase \(\Delta Q_y \approx -(0.20 ... 0.25)\)

\[
\begin{array}{|c|c|c|c|c|c|c|}
\hline
25\text{ ns} & \text{PSB inj} & \text{PSB extr/PS inj} & \text{PS extr/SPS inj} & \text{SPS extr/LHC inj} & \text{LHC top} \\
\hline
\text{Energy GeV} & 0.16 & 2 & 26 & 450 & 7000 \\
\text{Nb} & 1 & 1 & 72 & 288 & 2808 \\
\text{lb [e+ p+] } & 35.2 & 33.5 & 2.7 & 2.4 & 2.2 \\
\text{lb in LHC [e+ p+] } & 2.9 & 2.8 & 2.7 & 2.4 & 2.2 \\
\text{Exyn [mm.mrad]} & 1.9 & 2.0 & 2.1 & 2.3 & 2.5 \\
\hline
\end{array}
\]

\[B_f = 0.4 \rightarrow \Delta Q_y \approx -0.25\]
\[B_f = 0.3 \rightarrow \Delta Q_y \approx -0.37\]
Motivation

- Strict limitation of particle losses during injection and acceleration is crucial to avoid radiation damage in a proton machine with high beam power.

- This limitation requires reliable prediction / identification and proper correction the most dangerous lattice resonances, caused by the machine imperfections.

- To avoid significant growth of the emittance of the space charge dominated beam, the self consistent study of the low energy beam dynamics should be performed in the synchrotron with realistic representation the sources of the machine resonances.
Motivation

We need a tool to …

- describe the machine, including the high-order field and alignment imperfections
- be able to change the magnet and RF properties dynamically → MT injection & Acceleration
- analyze the single particle dynamics (‘lattice’ resonance study including the resonance compensation)
- analyze the multi particle dynamics, including the collective effects … in combination with different resonance compensation schemes
- analyze the beam properties (RMS emittance and the ‘halo’ formation) and particle losses around the machine
PTC-ORBIT combined code

Why PTC-ORBIT?

Real machine with field imperfections and alignment data

PTC lattice representation
- Comprehensive lattice analysis
- RF cavities (acceleration)
- NEW!... Time dependent magnets

ORBIT node
PTC as the tracker (6D integrator)

‘ORBIT’ staff:
- Injection foil.
- Space charge model.
- Transverse and longitudinal impedance.
- Feedback for stabilization.
- Aperture and collimation.
- Electron cloud model.

Main feature:
Common environment for the single particle dynamics (lattice analysis and resonance compensation) and multi particle dynamics (collective effects).
Polymorphic Tracking Code (PTC)

Symplectic Integration and Splitting (E. Forest, KEK)

PTC’s philosophy for symplectic integration is based on the work of Richard Talman (‘drift-kick’ model):

1. Split the elements in the lattice into integration nodes using one of PTC’s integration methods (the 2\textsuperscript{nd} method, the Ruth-Neri-Yoshida 4\textsuperscript{th} order method or the Yoshida 6\textsuperscript{th} order method)

2. Fit all the stuff you would normally fit using your matching routines

3. Examine the resulting lattice functions and perhaps some ‘short-term’ dynamic aperture

→ … after oscillating between steps (1) and (3), make up your mind and call that the ‘LATTICE’

... use MADX-PTC interface to prepare the beamline description → PTC FLAT file
Polymorphic Tracking Code (PTC)

‘ORBIT’ nodes by PTC

In the PTC flat file we can define a quantity ‘LMAX’ which represents the approximate minimal length between the nodes to introduce the collective effects.

PTC will group the ‘integration nodes’ of the node layout of PTC into groups whose length does not exceed the ‘LMAX’ length.

‘ORBIT’ nodes can be used to introduce the space charge, impedance effects and the diagnostic elements between the ‘trackable’ PTC blocks …
ORBIT (MPI)

- Developed by SNS to simulate the collective effects (space charge effects, impedance effects, electron clouds effects)
- Object-oriented open-source code (C++)
- Beam diagnostic, FOIL and APERTURE modules
- Parallel implementation
- ORBIT program is a script interpreter of the extended SuperCode program language
- Basic machine (lattice) description by MAD8
- Space charge kick:
  - Particle-In-Cell method
  - 2.5D or 3D model
  - Poisson solver → Fixed (with boundary) or Adjustable Grid (without boundary)

Jeff Holmes, jzh@ornl.gov
PTC-ORBIT combined code

- First discussion with the SNS group → ICFA HB06 workshop
- First test of the combined PTC-ORBIT code → 2007
- 2007 → first version of the code has been compiled for the KEK SuperComputers (Hitachi and IBM)
- PTC-ORBIT combined code has been used extensively for beam dynamics study for the J-PARC accelerators at the early stage of the Complex commissioning
- … study the different J-PARC Main Ring operation scenario for the case of high-power proton beam (up to 1.5MW at 30GeV )

- This work is supported by the Large Scale Simulation Program (FY2007-2013) of High Energy Accelerator Research Organization (KEK).

- 2011 → the PTC-ORBIT combine code has been compiled and tested for the CERN lxplus cluster → CERN LIU Project
- 2012 → … has been compiled and tested for the GSI cluster
CERN PS Booster

... main steps for 2012

CERN PS Booster study:

- ‘SHORT-dipole’ vs ‘NORMAL’ PSB lattice → emittance growth analysis ...
- Halo formation at the injection energy ... losses in realistic Aperture
- Effect of the double-harmonic RF system
- Effects of Basic machine imperfections & resonance correction scheme
- Benchmarking with existing results of the emittance measurements at the injection energy (160MeV)
- Acceleration process → ‘time’ scale of the emittance growth ...
- ‘Bare’ working point optimization during injection and acceleration
- Multi-turn injection scheme (with FOIL and ‘painting’ process) → dynamic variation of the machine properties during the injection process
CERN PS Booster … continue activity ‘2011’

… main steps for 2012

Christian plan (07-01-2012) for PS Booster team

- Effects of the short bending magnets in the injection section of PS Booster
- Multi-turn injection process taken into account FOIL and APERTURE (using the same machine parameters as for the ORBIT study … Matthias Scholz PhD thesis … C.Braco simulations)
- Benchmarking the simulations and measurements by using low-order resonances
- Introduction nonlinearities in to the PS Booster description (comments: (1) no data, which could be used to describe the field nonlinearities of the PS Booster; (2) observations of the resonance compensation could be used to provide the required data; (3) the resonance measurements using turn-by-turn data will be possible soon …)
CERN PS

... main steps for 2012

CERN PS study:

- Emittance growth and Losses
  - Injection process (with the 'dynamic' chicane variation)
  - Optimization of the ‘bare’ working point during the injection and acceleration

- Effects of machine imperfections and resonance correction

- Benchmarking with the emittance growth measurements

- Time scale of the emittance growth due to the combined effects of the machine resonances and the space charge during the injection / acceleration

- Effects of the longitudinal splitting at the injection energy
CERN SPS

... main steps for 2012

CERN SPS study:

- ... convergence study should be performed for the 'LHC'-type beam

- ... similar to the PS items #1b → #4...
PTC-ORBIT(MPI) code has been installed and compiled for the CERN lxplus cluster

PTC update is synchronized with the MADX update

Dedicated 10 multi-core computers are available for the group from June 2012 ('space charge' queue)

Basic PTC-ORBIT scripts have been prepared and uploaded into the Space-charge Group home-page

Batch script has been prepared and tested for the ‘spacecharge’ queue

Further code development (with support from E.Forest) ...

  → basic version (v0318) → for the convergence studies
  → v0413 → ‘FOIL’ issue has been solved
  → v1112 → current version of the code (with new implementations)
Dedicated ‘spacecharge’ queue ...

CERN PS / CPU time

ENGPARA batch cluster

Lxplus (batch)

Machine’s name
lxbsu2107
lxbsu2207
lxbsu2306
lxbsu2307
lxbsu2406
lxbsu2407
lxbsu2606
lxbsu2607
lxbsu2706
lxbsu2707

‘spacecharge’ queue (48p) ~ 20 sec

14.35 sec
12.06 sec
Current status of the group activity

Computational tools and hardware

04-12-2012
---> PTC TWISS modification ...

09-26-2012
---> 'MARKER' at the beginning of the machine layout ...

07-09-2012
---> to introduce the zero-length element for the
tracking --> to put FOIL at the beginning

08-09-2012
---> PTC bug with FLAT file

09-04-2012
---> Grid collision check is suppressed to avoid
observed (v088912) interruption the tracking

09-07-2012
---> modification: time unit for the PTC is [sec]
internally
but in Tables one can use any time-units
as before

---> FINAL_SETTINGS.TXT is changed
NO time-unit
---> checked for the machine with a few cavities
it should work

09-24-2012
---> some bug in the Normal Form part of PTC
used for the 'ts15a_ptc' procedure
by PTC-ORBIT is not affected

Alexander Molodozhentsev (KEK) Status Report / October 29, 2012

→... will be explained in the PTC-ORBIT node (updated version)
→... current version of the node:
PTC-ORBIT-v3.pdf / 04-25-2012
→... available through Internet:
/afs/cern.ch/user/a/amolodoz/public/PTC-ORBIT-NODES/
Current status of the group activity

MDs and benchmarking activity ...

Motivations (PS Booster, PS and SPS):

Started from May, 2012

- Machine study and collecting measured data for the benchmarking activity:
  - Effects of the low-order machine resonances
  - Resonance compensation schemes
  - Emittance evolution for the combined effects of the machine resonances and the low-energy space charge effects
  - Losses observations
  - Better understanding the current machine operation
Current status of the group activity

MDs and benchmarking activity …

PS Booster → 9 parallel MD sessions (160MeV+SpaceCharge)
LHC25 type beam → 180×10^{10} ppb

(1) Effects of the Integer resonance Q_x = 4 (static tune scan)
(2) Effects of the Montague resonance 2Q_x-2Q_y=0 (static tune scan)
(3) Effects of the LINEAR coupling resonance Q_x-Q_y=0
(4) RF manipulations to provide different bunching factor
(5) Static tune scan with ΔQ_{INC} ≈ -0.37
(6) Dynamic tune scan with ΔQ_{INC} ≈ -0.37
(7) Observation the resonance compensation

Benchmarking status:

Performed  In progress  In preparation
Current status of the group activity

MDs and benchmarking activity $\rightarrow [0,1,4]$ resonance

Double harmonic RF: $8+8$(in-phase)

$B_f \sim 0.23 \rightarrow \Delta Q_y^{INC} \approx -0.37$

Time variation of the vertical tune

Dynamic tune-scan
Current status of the group activity

**MDs and benchmarking activity** $\rightarrow [0,1,4]$ resonance

Double harmonic RF: 8+8(in-phase)

$B_f \approx 0.24 \rightarrow \Delta Q_{\text{INC}} \approx -0.37$

Double harmonic RF: 8+8(anti-phase)

$B_f \approx 0.4 \rightarrow \Delta Q_{\text{INC}} \approx -0.20$

Dynamic tune scan with $\Delta Q_{\text{INC}} \approx -0.35$

Losses start from $Q_x \approx 4.137$

Losses start from $Q_x \approx 4.10$

... $Q_x$ moved away from 4.10
Current status of the group activity

MDs and benchmarking activity $\rightarrow [0, 2, 9]$ resonance

$\rightarrow \ldots$ in preparation to make the simulations with APERTURE
Current status of the group activity

‘Space-charge’ convergence study

- ORBIT(MPI) is the PIC code
- in particular, FFT Particle-In-Cell without (adapted grid) or with (fixed grid) the boundary
- Opium set of the required parameters for the ‘space-charge’ model
- avoid artificial emittance growth (core and halo parts of the beam)
- reasonable CPU time per the ‘1 turn’ tracking
- $N_{max} (x, y), N_{rep}, l_{run}$ $N_{max}$ should be optimized for beams with different parameters (LHC type or CNGS type)

Machine lattice:
- PSB → basic IDEAL lattice without any errors (static lattice)
- PS → basic IDEAL lattice → NO any correctors
- SPS → basic IDEAL lattice
- RCS → basic IDEAL lattice

PTC-ORBIT(MPI)

<table>
<thead>
<tr>
<th>Method</th>
<th>$L_{max} / N_{rep}$</th>
<th>$N_{max} (x, y)$</th>
<th>$N_{max} \times 10^5$</th>
<th>$l_{run}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSB</td>
<td>Fixed grid</td>
<td>1m / 199</td>
<td>256</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Adapted grid</td>
<td>1m / 199</td>
<td>64</td>
<td>500</td>
</tr>
<tr>
<td>PS</td>
<td>Fixed grid</td>
<td>10m / 70</td>
<td>1024</td>
<td>250</td>
</tr>
<tr>
<td>SPS</td>
<td>Adapted grid</td>
<td>3.32m / 2688</td>
<td>64</td>
<td>200</td>
</tr>
<tr>
<td>RCS</td>
<td>Adapted grid</td>
<td>1m / 157</td>
<td>128</td>
<td>500</td>
</tr>
</tbody>
</table>

Space charge detuning for CERN PS-Booster (160MeV)

2D histogram $Q_{x}/Q_{y} = 4.26/4.43$

A. Molodozhentsev (KEK), ICFA HB12 workshop
Beijing, China, September 17-21, 2012
Current status of the group activity

‘Simulation’ activity (PS Booster): benchmarking

Motivation:
- reproduce the measured beam evolution at 160MeV by the PTC-ORBIT tracking

Foot print
Q_{H}/Q_{V}=4.18/4.23
LHC25 beam
B_{t} \sim 0.4

Generated and measured transverse beam profile at the 160MeV energy

Measured beam profile
'Tomoscope' image

Generated beam profile
Current status of the group activity

‘Simulation’ activity (PS Booster): benchmarking

... taken into account the random error of the quadrupole strength of the PS Booster magnets

- lattice with RANDOM errors \{\delta K1\}QM
  - #1: ‘ideal’ lattice
  - #2: 1Sigma = 1.0 \times 10^{-3} (relative value)
  - #3: 1Sigma = 5.0 \times 10^{-3}

... including the random TILT of the PS Booster quadrupole magnets

Up to 1Sigma = 4.28 \times 10^{-5} rad

Linear coupling of the PS Booster:
\[ \Delta Q_{\text{MIN}} \approx 0.008 \]
Current status of the group activity

‘Simulation’ activity (**PS Booster**): short-bends

The shorter bending magnets at injection ...

Courtesy V.Forte

→ Simulations should be continued to check effects of the [0,2,9] resonance
Current status of the group activity

- Multi-turn injection for the CERN PS Booster with LINAC4

- Significant improvement of the efficiency of the MT injection by using the H⁺ stripping injection in the H-plane
- Control over both transverse emittances
- Effects of the edge-focusing of the ‘slow’ bump-magnets, changing during the chicane reduction

### KSW Parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC Beam</th>
<th>CNGS Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ₁</td>
<td>7 us</td>
<td>10 us</td>
</tr>
<tr>
<td>τ₂</td>
<td>20 us</td>
<td>49 us</td>
</tr>
<tr>
<td>τ₃</td>
<td>35 us</td>
<td>64 us</td>
</tr>
</tbody>
</table>

Kₑ: current corresponding to a bump height at the foil of ~35 mm

Kicks for a 55 mm bump at the foil:
- KSWF16L1: 8.74 mrad → 0.045 T
- KSWF14L1: 2.55 mrad → 0.013 T
- KSWF12L1: 2.55 mrad → 0.013 T
- KSWF16L4: 8.74 mrad → 0.045 T

Functions have to be defined for varying the dI/dt of the KSW during injection.
Different functions for different users → high flexibility is required.
Current status of the group activity

Multi-turn injection process for the ‘LHC25’ type of beam

- ‘20 turns’ injection
- generated distributions for each beamlet
- ‘Matched’ injection process
- Ideal lattice of CERN PS Booster ($Q_H=4.28$, $Q_V=4.55$)
- ‘Time variation’ of the injection chicane by KSW and BSW (realistic lattice description)
- RF system: double harmonic with acceleration at the injection
- ACTIVE vertical beta-beating compensation during the chicane reduction
- FOIL and APERTURE are taken into consideration (first attempt)
- Long-term tracking
Current status of the group activity

LHC type beam: beamlet injection

Horizontal phase-plane ($x$[mm], $x'$[mrad])

Estimations ...

Effect of the stripping foil (no aperture limit implemented)

$\varepsilon_H (\text{rms, norm}) \sim 1.319\pi \text{ mm.mrad}$

$\varepsilon_V (\text{rms, norm}) \sim 1.333\pi \text{ mm.mrad}$

(without foil)

$\varepsilon_H (\text{rms, norm}) \sim 1.328\pi \text{ mm.mrad}$

$\varepsilon_V (\text{rms, norm}) \sim 1.336\pi \text{ mm.mrad}$

(with foil)

0.03% lost

0.01% lost

Courtesy M. Martini
Current status of the group activity

LHC type beam: beamlet injection

Foil and no aperture

Core 99.97%

0.03% lost (-100mm < x < -85mm)

Histogramme function (x-axis, mm)
Probability distribution function

Cumulative distribution function (x-axis, mm)

Effect of the stripping foil (no aperture limit implemented)

Courtesy M. Martini

Alexander Molodozhentsev (KEK)
Current status of the group activity

LHC type beam: tracking up to ~ 20msec

Capture efficiency ~ 98%, $B_f \sim 0.6$

Aperture limit implemented for tracking after beamlet’s injection

Cumulative distribution function ($\Delta E$-axis, GeV)  Longitudinal phase-plane ($\varphi$[rad], $\Delta E$[GeV])

Beam-scope window

Beam at turn 20020
Beam at turn 20 (after beamlet injection)

RF bucket

Particles lost on aperture limits

Courtesy M. Martini
Current status of the group activity

LHC type beam: tracking

Normalized transverse rms emittances [mm.mrad] vs time [μs]

Normalized transverse 95% and 99% emittances [mm.mrad] vs time [μs]

Aperture limit implemented for tracking after beamlet’s injection

Courtesy M. Martini
Current status of the group activity

PTC-ORBIT

- A convergence study has been done and the simulation parameters have been set for LHC-50 beam and ideal latice.

- Operational LHC-50 (August 2012):
  \[ 105 \times 10^{10} \text{ p/b} ; \ \epsilon_{\text{normalized}} = 1.5 \mu \text{m}; \ \Delta p/p(1\sigma) = 1.25 \times 10^{-3}; \ \text{full bunch length} = 180 \text{ ns} \]
  Working point (6.235 ; 6.245)

Laslett tune-spread:
\[ \Delta Q_{x,y} = \frac{r_p N_b}{(2\pi)^{3/2} \gamma^3 \beta^2 \sigma_z} \int_{s_{x,y}} \frac{\beta_{x,y}(s) ds}{\sigma_{x,y}(s)[\sigma_x(s) + \sigma_y(s)]} = (0.19; 0.28) \]

- From PTC-ORBIT:

\[ Q_y \]

\[ Q_x \]

\[ \sim 0.28 \]

\[ \sim 0.2 \]

- Very good agreement
Current status of the group activity

B. I. Including errors in MAD lattice

- Magnetic & alignment errors are essential for Space Charge studies because at low energy (bare machine) they are the main cause of resonance excitation, and cause therefore losses and emittance growth
- PS is implemented in MAD with ideal lattice
- In MAD the main magnets are divided in 4 half units 2D & 2F \( \rightarrow \) 400 elements
- Main magnetic errors have been implemented in MAD. For each half unit one set of multipolar field errors is created, i.e., 400 numbers per multipolar field error have to be generated \( \rightarrow \) ... up to octupole component (normal and skew)

- Skew sextupole coupling resonance
- Linear coupling resonance
- Montague resonance
- 3Q\(_x\) resonance

Observation by analysing Turn-by-Turn data \( \rightarrow \) in progress
Current status of the group activity

B. II. Verification and calibration

- Benchmark between lattice with errors and experimental data:
  - Loss due to skew sextupole resonance over 25ms (MD 06/08/2012), Ramp \(Q_y = 6.24; \ Q_x = [6.34 : 6.38]\)

- PTC-ORBIT simulation using the lattice with magnetic error:

  Losses in the machine (MADX aperture definition) during the tune-scan process

- Alignment errors have been introduced which gave a realistic closed orbit \((Xco=4mm, Yco=1mm)\) and a simulation of the resonance scan is currently running.
Current status of the group activity

Resonance observation

‘LHC-INDIV’ beam

Beam centroid evolution
\( \rightarrow \) LINEAR coupling \( \rightarrow [1,-1,0] \)

H-kick only
\( Q_x = 6.20 \)
\( Q_y = 6.21 \)

Observation of the \([1,-1,0]\) resonance
\( \rightarrow \) turn-by-turn data acquisition ...

[1,-1,0] resonance observation

Linear coupling resonance observation (NO correction)

Turn-by-Turn data analysis

Alexander Molodozhentsev (KEK)

Status Report / October 29, 2012
Current status of the group activity

SPS MDs for the code’s benchmarking

Estimation of space charge tune spread

Horizontal

Vertical

• Approaching the integer resonances leads to
  - Emittance blow up in the respective plane
  - A reduction of losses in the horizontal plane
  - Increasing losses in vertical plane

• For $2.7e11 \text{p/b}$ and about $(\varepsilon_x + \varepsilon_y)/2 \approx 1.0$-1.2μm injected

High-intensity beam

$\Delta Q_x = 0.15 / \Delta Q_y = 0.25$

‘Q20’ optics

Courtesy H Bartosik
Current status of the group activity

SPS MDs for the code’s benchmarking

Emittance growth for $Q_x$ close to integer


‘Q20’ optics

$Q_x = 20.07$

- Same beam parameters as on 24.05.2012 (see above)
  - Initial tune spread is about
    - $\Delta Q_x = 0.15$ / $\Delta Q_y = 0.25$
  - (lossless) blow up of the core
    - $\varepsilon_x > 2 \mu m$ after 40 ms
    - $\varepsilon_x > 4-5 \mu m$ after 400 ms

Courtesy H. Bartosik

Alexander Molodozhentsev (KEK)
Current status of the group activity

SPS MDs for the code’s benchmarking

Behavior close to integer resonances

- Parallel MD: short flat bottom cycle
- Standard LHCindiv bunch: $1.2\times10^{11}/b$ with $(\varepsilon_x+\varepsilon_y)/2 \approx 1.2\mu$m
  - Expect $\Delta Q_x \approx 0.07/\Delta Q_y \approx 0.11$

Low-intensity beam

‘Q20’ optics

Large aperture in horizontal plane allows for huge emittance blow-up without losses

Aperture limitations in vertical plane lead to increasing losses with vertical beam size

Courtesy H. Bartosik

Alexander Molodozhentsev (KEK)
Current status of the group activity

- **RCS conceptual design**

Motivations (including the space charge at injection):
- alternative to the CERN PS Booster upgrade (160MeV-2GeV, 10Hz)
- effect the beam envelope modulations on the emittance growth
- effect of the super-periodicity

\[ \Delta Q_v \approx -0.4 \]

- Lattice tune above \( 2Q_v = 7 \)
- Including the Vertical beta-beating correction …

Variation of the beam size can lead to the emittance growth:
- the ‘TRIPLET’ features smallest variation of the transverse emittance compared to the ‘DOUBLET’ and the ‘FODO’ cell

Emittance growth due to excitation of ‘systematic’ resonances:
- ‘weak’ symmetry breaking in one cell with correcting the beat-beat

Courtesy M. Fitterer
Current status of the group activity

Measurements to be used for the simulations (to avoid assumptions) ...

A new way to match the longitudinal distribution (thanks to S. Hancock)

---

Very useful in case of “particular” longitudinal shapes (filamentation, acceleration,...)
Current status of the group activity

Pre-simulated 6D distribution of the H\(^-\) beam from LINAC4 (micro-bunch) at the injection point of PS Booster

→ … should be used as the 6D distribution to study the multi-turn injection

Courtesy A.Lombardi
To predict the performance of the injectors after LS2, it seems that several questions still need to be answered:

- Full simulations of the H− injection at 160 MeV into the PSB have to be set up to determine realistic curves of transverse emittance versus intensity and fully justify the usual assumption that the brightness of the beams will be increased by a factor two.

- The PSB machine studies necessary to set up these simulations (i.e., those leading to a benchmarked nonlinear optics model of the PSB at 160 MeV) are still missing, even if an effort has been undertaken to describe the machine at 160 MeV in strong space charge regime.
Next steps in the group activity

**CERN PS Booster (1) → with V.Forte, M.Martini, E.Benedetto**

- Check the simulations, performed by Chiara Bracco and Matthias Scholz for multi-turn injection from LINAC4 into PS Booster, taken into account the FOIL and APERTURE effects

- Multi-turn injection process to provide different beams from PS Booster (from LHC to CNGS beam)

- Continue study (data accumulation) of the emittance evolution and the particle losses in PS Booster at 160MeV energy for the space-charge dominated beam (LHC type beam)

- Emittance evolution at different energies for the case of the space-charge dominated beams from LINAC2 (measurements and simulations)
Next steps in the group activity

CERN PS Booster (2) → with V.Forte, M.Martini, E.Benedetto

- Benchmark the particle losses around the machine for the LHC25 type beam at 160MeV energy
  → Closed Orbit Reconstruction at different energies to reproduce measurements

- Study the resonance excitation and compensation at different energies
  PS Booster lattice imperfection (based on the measurements of non-linear resonances)

- Collaboration with the LINAC4 group (A.Lombardi) ‘H- beam parameters for the PS Booster multi-turn injection’
  → use the realistic 6D distributions, required for each beam from PS Booster
Next steps in the group activity

CERN PS Booster (3) → with V.Forte, M.Martini, E.Benedetto

- Mismatching and Injection errors as sources of the emittance growth
  → simulations and measurements (for 50MeV injection)
  → simulations for 160MeV beam

- Effects of field errors and nonlinear field components on the emittance growth and particle losses
  → eddy current effects in the bump magnets with the ‘inconel’ chamber

- Optimization of the ‘bare’ working point for different beams (LHC → CNGS)
  ...

Alexander Molodozhentsev (KEK)
Next steps in the group activity

CERN PS (with Raymond Wasef)

- Resonance study: measurements and simulations
- Reconstruction the closed orbit distortion
- Effects of the injection errors: measurements and simulations
- Improvement the machine description (field nonlinearities and alignment errors)
- Optimization the ‘bare' working point for different beam parameters
- Particle losses around the machine
Next steps in the group activity

CERN SPS (with Hannes Bartosik)

- Identify machine resonances (MDs) by the ‘probe’ beam
- Develop nonlinear machine model in MADX/PTC
  - closed orbit, nonlinear chromaticity, multipole of main magnets, misalignments …
- Benchmark machine model with integer resonance (experimental data with space charge dominated beam)
- Experimental explore the tune diagram with the space-charge dominated beam
  (with LIU required space charge tune spread)
  - find ‘promising’ working point region (with minimum emittance blow-up and losses)
  - identify relevant (limiting) resonances
- Specific studies of relevant resonances
  - measure resonance driving terms
  - study and model beam behavior close to resonances (losses, emittance blow-up, bunch shortening …)
  - study possible compensation schemes using non-linear elements
Thanks for your attention