Towards the Description of Long Term Self Consistent Effects in Space Charge Induced Resonance Trapping

G. Franchetti, GSI
ICAP 2006, Chamonix
Overview

High intensity challenges

Impact on computer simulations

Trapping of particle induced by space charge

Status of the art of long term simulation
Computing & Modeling

Modeling of Complex Systems (analytic, numeric)

Physical Problem

Theorist Path

Understanding

Prediction

Results (observables)

Experiment

Experimentalist path
High Intensity beams are needed in future research

JPARC
Storage for 25000 turns of Bunches with tuneshift
$\Delta Q \sim 0.17-0.28$

SNS (J. Holmes)
Design intensity $1.4 \times 10^{14}$ protons
Stored for 1000 turns

CERN: LHC beam in PS
Space charge effect not neglectable

Courtesy E. Metral
HHH CERN-GSI workshop

LOSES IN THE PS
('% of the inj. beam')

TIME IN THE CYCLE [ms]

9.2 $10^{12}$ ppp @ 26 GeV/c
(01/09/04)
The next generation of computational challenges at FAIR

- New: Cooled pbar Beams (15 GeV)
- Intense Cooled Radioactive Beams
- Parallel Operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Increase Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Beam Intensity</td>
<td>x 100-1000</td>
</tr>
<tr>
<td>Secondary Beam Intensity</td>
<td>x 10 000</td>
</tr>
<tr>
<td>Heavy Ion Beam Energy</td>
<td>x 30</td>
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SIS100 critical scenario

**Required Intensity in SIS18 Booster**

(after acceleration)

\[1.5 \times 10^{11} \text{ U}^{28+} \text{-ions /cycle}\]

**Required Intensity in SIS100**

\[6 \times 10^{11} \text{ U}^{28+} \text{-ions /cycle}\]

**Beam Life Time**

Low charge states beams provide higher intensities but have shorter life time

1 second Storage of The first bunch
Requirements on Beam loss

SIS 100/300 average (peak) power:

\[ 6 \times 10^{11} \text{s} \ 1.0 \text{ GeV/u } U^{28+} : 23 \text{ kW} \]

1 W/m tolerable beam loss

\[ \sim 5 \% \text{ acceptable loss} \]
The SIS100 challenges

Storage time 5 x 10^5 turns
Intensity 1.5 x 10^{11}/ions U^{+28}
Space charge tuneshift \Delta Q \sim 0.2
SIS100 has SC dipoles --> Nonlinearities

Beam loss prediction
Localization of beam loss
Emittance increase prediction

Lattice design:
Collimation system

Magnet quality:
Nonlinear field control

Resonance compensation system

Coherent instability threshold with space charge in the FAIR rings. Talk on Wed. by O. Boine-Frankenheim
The physics problem

Periodic crossing
Of a resonance

Bare tune
Resonance
Trapping into Resonances

Periodic crossing
Of a resonance

Bare tune

Resonance
Computing challenges

**PIC parameters**
Grid resolution of the beam: +/- 10 grid points
Typical beam pipe/beam size ratio = 6
Transversally 125 x 125 grid points
Longitudinally keep the same 125 grid points
Statistical fluctuation of 1% -> $10^4$ particle/grid cell

**Integration steps/turn:** $20 \times Q_x = 20 \times 18 = 360$

**Tracking a bunch for $5 \times 10^5$ turns means:**
Compute the space charge of $100 \times 10^6$ particles
for $200 \times 10^6$ integration steps

N = $100 \times 10^6$ particles
The long term effect of PIC noise

Periodic Quadrupole Channel, $\sigma_0 = 60^\circ$, $\sigma = 15^\circ$

J. Struckmeier Phys. Rev. E 54, 830–837
Modeling: Example with SIS18

AG lattice modeled
In smooth approximation

Uniform focusing transport channel

\[ k_x = \left( \frac{Q_x R_0}{R} \right)^2 \]

\[ x'' + k_x x = 0 \]
Beam distribution

\[ \rho(x, y, z) \propto \exp \left( -\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2} \right) \]

Matched with a 3D uniform focusing system
Modeling of space charge and lattice nonlinearities

Lattice Nonlinearities (in 2D)

\[
\begin{pmatrix}
x \\
x'
\end{pmatrix} \rightarrow \begin{pmatrix}
x \\
x' + k_n x^n
\end{pmatrix}
\]

Analytic space charge modeling

\[
E_x(x, y, z) = Ke^{-z^2/(2\sigma_z^2)} \frac{x}{r^2} \left[1 - e^{-r^2/(2\sigma_x^2)}\right]
\]

* Round beam
* Frozen distribution

Local Longitudinal density
Single particle equation of motion

\[
\begin{aligned}
    x'' + \left( \frac{Q_{x0}}{R} \right)^2 x &= Ke^{-z^2/(2\sigma_z^2)} \frac{x}{r^2} \left[ 1 - e^{-r^2/(2\sigma_x^2)} \right] + K_2(s)(x^2 - y^2) \\
    z'' + \left( \frac{Q_{z0}}{R} \right)^2 z &= 0
\end{aligned}
\]

Symplectic tracking

Space charge kicks

Lattice
Nonlinear kick
Example for SIS18

\[ R = 34.4 \text{ m} \]
\[ Q_{x0} \sim 4.3 \]
\[ Q_{y0} = 3.2 \]
\[ \sigma_{x/y} = 1 \text{ cm} \]
\[ \Delta Q_x = 0.1 \]
\[ K_2 = 0.05 \text{ m}^{-2} \]

Phase space plot of the frozen system at \( z = 0 \)

Correlation instantaneous island position versus longitudinal position

The outer position of the island is reached at \( z = 0 \) and it depends on \( Q_x - Q_x,\text{res} \). Here \( Q_x = 4.35 \)
A particle with maximum amplitude of $x = 1.5 \sigma_x$ will see the island crossing its orbit at $z = 1.6 - 1.7 \sigma_z$

The larger the particle maximum amplitude, the smaller the longitudinal position where the island crosses the particle’s orbit.
Example of full trapping
In 1 synchrotron oscillation

15000 turns for 1 oscillation

\[ x = 1.5 \sigma_x, \quad x' = y = y' = 0 \]
\[ z = 3 \sigma_z, \quad z' = 0 \]
\[ Q_x = 4.35 \]
Halo formation

\[ Q_x = 4.35 \quad x = 1.5 \sigma \quad x' = y = y' = z' = 0 \quad z = 3 \sigma \]

Mechanical limitation
Consequences on the evolution of the bunched beam

Emittance growth

Halo Size

Halo density

How to simulate such a complex dynamics?
# The Universe of Codes

F. Zimmermann et al. EPAC2006  
http://oraweb.cern.ch:9000/pls/hhh/code_website.startup

## Optics
- BETA
- LieMath
- MADX
- SAD
- SixTrack

## Intrabeam Scattering
- MADX
- MOCAC

## Conventional Instabilities
- HEADTAIL
- MOSES
- ORBIT
- TRISIM
- WARP

## Electron Cloud
- Build-Up Simulations
  - CSEC
  - ECloud
  - Faktor2
  - POSINST
- Incoherent
  - HEADTAIL
  - MICROMAP
- Multi-Bunch Instability Simulations
  - PEI-M

## Multipacting
- ESA ESTEC

## Self-Consistent Simulations
- Faktor2
- ORBIT
- QUICKPIC
- WARP

## Single-Bunch Instability Simulations
- HEADTAIL

## Synchrotron Radiation
- PHOTON

## Vacuum
- VAKDYN
- VAKLOOP
- VAKTRAK

## Impedances
- ABCI
- LAWAL
- LAWAT
- PATRIC
- REWALL

## Electron Cooling
- BETACOOL
- MOCAC
- VORPAL

## Luminosity Performance
- EVOL

## Impedances
- ABCI
- LAWAL
- LAWAT
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- REWALL

## Nonlinear Dynamics
- Ctrack
  - MICROMAP
  - NAFF
  - NERO
  - PLATO
  - SODD
  - SUSSIX
  - SixTrack

## Space Charge
- IMPACT
- MICROMAP
- ORBIT
- PATRIC
- Simpsons
- Simpkins
- WARP

## Intrabeam Scattering
- BBSS
- BEAMX
- BeamBeam3D
- COMBI

## Strong-Strong
- BBSS
- BEAMX
- BeamBeam3D
- COMBI

## Weak-Strong
- BBSIM
- BBTrack
- WSDIF

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MICROMAP Library

Nonlinear kick

Arbitrary linear map transport

2D PIC solver: Square or arbitrary boundary
Nonlinear kicks: Lattice nonlinearities
Space charge
Frozen space charge modeling

A. Orzekhovskaya poster

For beam of arbitrary sizes the modeling is more complex

\[
E_x = \frac{Q}{2} x \sum_{l=0}^{N} c_l \sum_{i+j+k=l} \frac{l!}{i!j!k!} I_{i+1,j,k} x^{2i} y^{2j} z^{2k}
\]

\[
\hat{n}(t) = \sum_{l=0}^{N} c_l t^l
\]
Benchmarking / Validation

Physical Problem

Code1 (modeling)  Code2 (modeling)

Experimental Result

Brute force modeling? Step-by-step modeling?

Code-code Benchmarking

Modeling-Physics Benchmarking
Emittance evolution in a full bunch

SIS18 (full AG lattice)
$Q_s = 10^{-3}$
$10^5$ turns
$10^3$ macroparticles

In SIMPSONS (S. Machida)
the longitudinal dynamics
is nonlinear

In MICROMAP (G. Franchetti)
the longitudinal dynamics
is linear

Excellent Agreement !!

G. Franchetti, I. Hofmann, S. Machida HB2006

http://www-linux.gsi.de/~giuliano/research_activity/trapping_benchmarking/main.html
Simulations of the CERN-PS Experiment

Modeling-Experiment Benchmarking

 Including chromaticity

\[
\frac{\varepsilon_x}{\varepsilon_{x0}} \text{ Sim.} \\
\frac{I}{I_0} \text{ Sim.} \\
\frac{\varepsilon_x}{\varepsilon_{x0}} \text{ Exp.} \\
\frac{I}{I_0} \text{ Exp.}
\]

16% beam loss

 Without chromaticity

\[
\frac{\varepsilon_x}{\varepsilon_{x0}} \text{ Sim.} \\
\frac{I}{I_0} \text{ Sim.} \\
\frac{\varepsilon_x}{\varepsilon_{x0}} \text{ Exp.} \\
\frac{I}{I_0} \text{ Exp.}
\]

9% beam loss

Maximum beam loss do not match measurements

G.Franchetti, I.Hofmann, M.Giovannozzi, E.Metral, M.Martini
E-cloud incoherent effects

Periodic crossing of resonances and particle trapping Induced by EC pinch

$\sigma_e = 0.5 \sigma_b, \Delta Q_{\text{max}} = 0.04$

E. Benedetto, G. Franchetti, F. Zimmermann
PRL, 97, 034801 (2006)
The complexity of the self-consistency

- Detuning
- Resonance condition
- Particle amplitude growth
- Beam size growth
- Particle loss

*Halo particles*
Including beam loss effect

This prediction is not correct because the effect of the self-consistency is very critical on how many particles are pushed into the resonance.

CF modeling of PS Including chromaticity

2x10^6 turns
Measurement at CERN-PS

Attempt of long Term beam loss Prediction including Semi-self consistency
4x10^5
Effect of beam loss

Particles which
Cross the resonance
Are trapped and lost

New particle are
Pushed into a periodic
Resonance crossing

The result on long term beam loss are sensitive
To the modeling on how new particles are drawn
Close the resonance.

ISSUES: better modeling and further Experiment-code Benchmarking
Benchmarking Experiments @ GSI

Experiment S317

- 4 Measurement campaign starting from December 2006.
- 24 shifts of beam

Controlled highly resolved measurement data will be available for benchmarking codes, on emittance growth and beam loss perdition.
Conclusion / Outlook

Understanding of the main Ingredients of the long term Storage of high intensity bunches

Developed a modeling which Gives result consistent with Measurements

Work for including the effect of the Self consistency is in Progress

At GSI measurement for code Benchmarking will be performed As part of an approved experiment