Modeling High Intensity Beams in Cyclotrons

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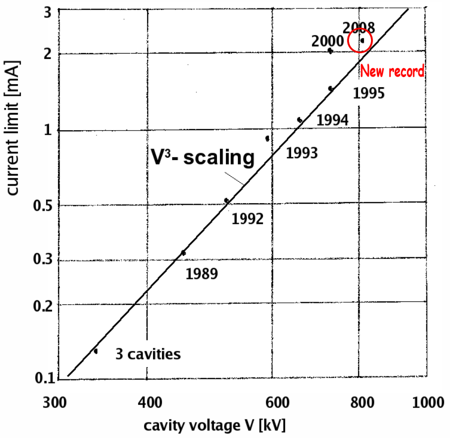
Outline

Background: History

In the past decades, new applications motivated the need of cyclotrons with higher beam intensity, in which space charge strongly affects the beam dynamics.

It is important to study its influence by means of quantitative modeling.



Space charge limits in 590 MeV Ring cyclotron (courtesy by W. Joho, 1981)

Background: Brief review of space charge studies

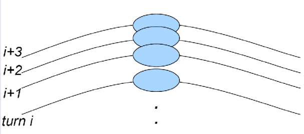
Analytic Models

- Disk model by M.M.Gordon (1970s)
- Sector model by W.Joho (1980s)

Numerical solution

- 2D serial PIC codes: PICS, PICN by S.Adam and S. Koscielniak (1990s)
- 3D Parallel PIC codes: MAD9P by A.Adelmann & LIONS SP by P.Bertrand (2000s)

Neighboring bunch effects ⇒ Not much work has been done yet.
E.Pozdeyev introduced "auxiliary bunch" in his serial code CYCO (2003).

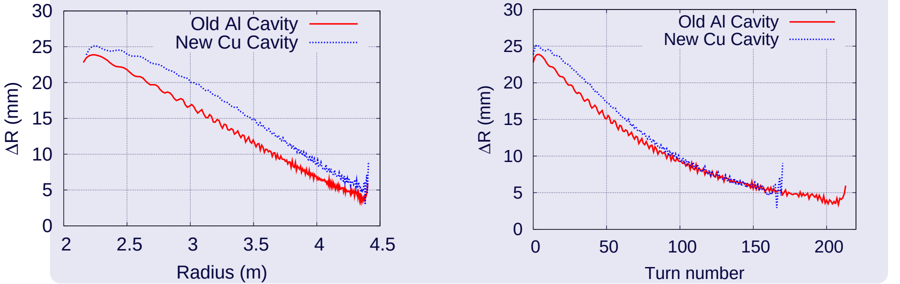


Motivation: Upgrade Project of PSI Cyclotron Facility

590 MeV Ring (CW)

- Beam Current/Power:
  2mA/1.2MW ⇒ 3mA/1.8MW
  The highest beam power cyclotron in the world
- Turns number:
  200 ⇒ less than 160
- After upgrade, turn separation bigger

Motivation: Upgrade Project of PSI Cyclotron Facility



After upgrade

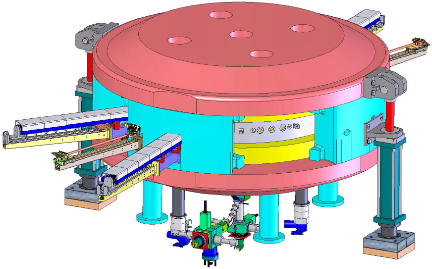
- ΔR is still at the same order of magnitude as bunch's radial size
- I increases from 2 mA to 3mA

$\Rightarrow$ Neighboring bunch effects will increase!

Motivation: Compact Cyclotron under Construction at CIAE

100MeV H^- CYCIAE-100

- Designed beam current 0.2mA, future 0.5mA
- Turns number is about 500
- Energy gain per turn is 0.2MeV
- Multi-turn extraction by stripper at radius of 1.9m
- At extraction point,
  $\Delta R_{n,n+1} = 1.5\text{mm}$
  Far smaller than beam size, multi-bunches will overlap



Outline

Introductions to OPAL-CYCL

- 3D parallel PIC code for cyclotrons
- Based on several other framework (IPPL, CLASSIC, H5Part, HDF5)
- Use time as independent variable
- Solve Poisson equation with spectral methods
- Use 4th-order RK as the integrator
- Track in global Cartesian coordinates
- Store intermediate phase space data in H5Part format
- Has three working modes:
    - Single particle tracking mode
    - Tune calculation mode
    - Multiple particles tracking mode including space charge effects

Equations of Motion

Equations of motion of single charged particle in electromagnetic field:

$$\dot{\mathbf{p}} = \mathbf{F}(\mathbf{v}, \mathbf{x}, t) = q\ (\mathbf{v} \times \mathbf{B} + \mathbf{E}),$$

$$\mathbf{E} = \mathbf{E}_{\rm ext} + \mathbf{E}_{\rm self},$$

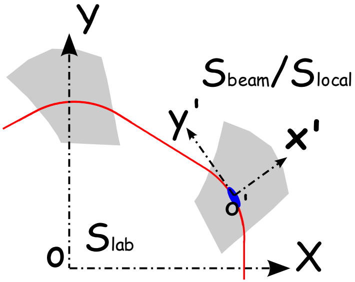
$$\mathbf{B} = \mathbf{B}_{\rm ext} + \mathbf{B}_{\rm self}.$$

Two assumptions are valid for Cyclotrons

- Wake field & image charge effects are far smaller than space charge
- Particles relative motion in a bunch is non-relativistic

$\mathbf{E}_{\rm ext}$, $\mathbf{B}_{\rm ext} \Leftarrow$ measured field map or commercial software,
$\mathbf{E}_{\rm self}$, $\mathbf{B}_{\rm self} \Leftarrow$ solve Poisson equation.

The Coordinates Frames

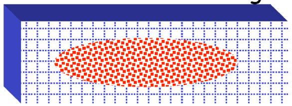


3 frames defined

- $\mathbf{S}_{\mathrm{lab}}$: The global lab frame
- $\mathbf{S}_{\mathrm{local}}$: The local instantaneous frame
- $\mathbf{S}_{\mathrm{beam}}$: The beam rest frame

3D Parallel Poisson Solver: P-M/FFT methods

Space charge fields can be obtain by solving the Poisson equation using Particle-Mesh (P-M) methods.



Solve Poisson equation on a rectangular domain with open BC

A 3D rectangular grid which contains all particles is built (following quantities with superscript of D means on grid). The solution of the discretized Poisson equation with $\vec{k} = (l, n, m,)$

$$\nabla^2 \phi^D(\vec{k}) = -\frac{\rho^D(\vec{k})}{\epsilon_0}, \vec{k} \in \Omega^D$$

ϕ^D is given by convolution with the appropriate discretized Green's function G_D:

$$\phi^D = \rho^D * G^D$$

3D Parallel Poisson Solver: P-M/FFT methods

Typical Procedure of the Poisson Solver

- ▷ Assign all particles charges q_i to nearby mesh points to obtain ρ^D
- ▷ Lorentz transform to obtain ρ^D in $\mathbf{S}_{\mathrm{beam}}$
- ▷ Use FFT on ρ^D and G^D to obtain $\widehat{\rho}^D$ and $\widehat{G}^D$
- ▷ Determine $\widehat{\phi}^D$ on the grid using $\widehat{\phi}^D = \widehat{\rho}^D \cdot \widehat{G}^D$
- ▷ Use inverse FFT on $\widehat{\phi}^D$ to obtain ϕ^D
- ▷ Compute $\mathbf{E}^D = -\nabla \phi^D$
- ▷ Interpolate $\mathbf{E}$ at particle positions $\mathbf{x}$ from $\mathbf{E}^D$
- ▷ Lorentz back transform to obtain $\mathbf{E}_{\mathrm{sc}}$ and $\mathbf{B}_{\mathrm{sc}}$ in $\mathbf{S}_{\mathrm{lab}}$

Neighboring Bunch Effects: Multi-bunch model

Multi-bunch model

In our model, the injection-to-extraction simulation is divided into two stages,

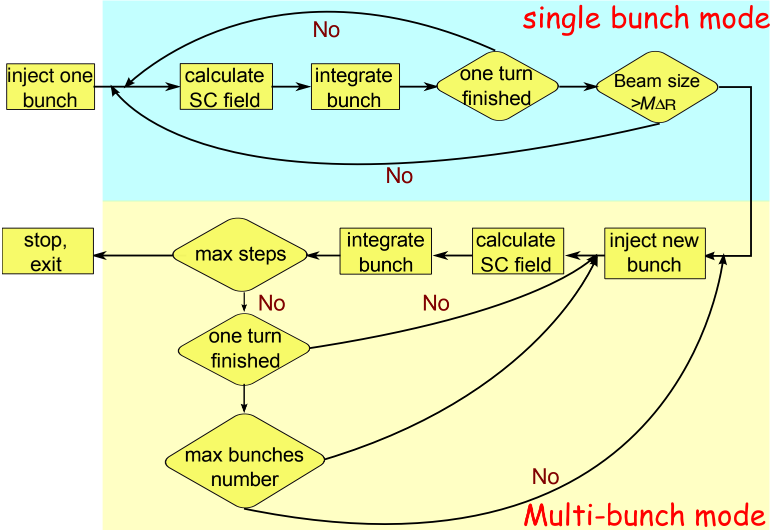
- First stage, big $\Delta R \Rightarrow$ single bunch tracking
- Second stage, small $\Delta R \Rightarrow$ multiple bunches tracking

The working mode transfers from single bunch mode to multiple bunches mode automatically when ΔR is comparable with the size of bunch.

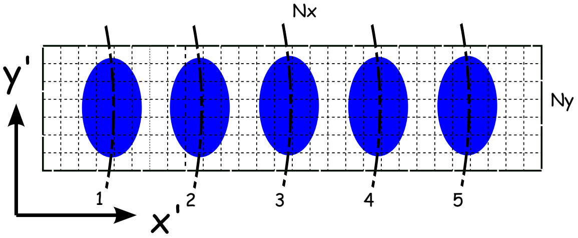
Summary

- Fully self-consistent model of dealing with radially neighboring bunches effects in time domain
- Using multiple bunches simulation, neighboring bunch effects can be evaluated precisely

Neighboring Bunch Effects: Algorithm



Neighboring Bunch Effects: Algorithm



Energy bins

- One energy bin for each bunch
- All particles grouped into bins
- Compute each bin's contribution separately
- Rebin when energy spread exceeds a given threshold value

Outline

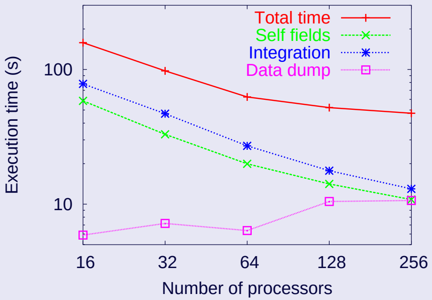
Parallel Scalability: Test on Cray XT3 at CSCS, Switzerland

Setup

- 10^6 particles,
- 3D FFT on a 64^3 grid,
- 2D domain decomposition
- Track 200 time steps
- Gaussian distribution
- Dump data into single H5Part file every 10 steps

Observations

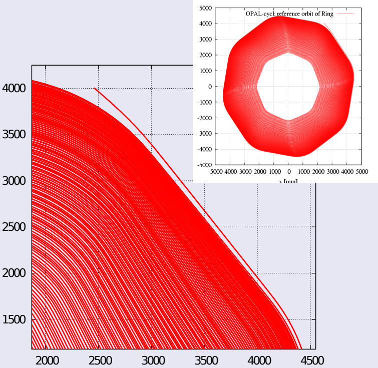
- The code scales well
- Good load-balancing
- Dumping time increased

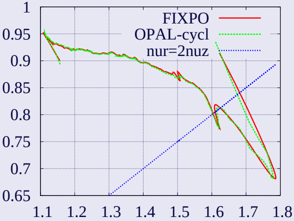


Time to solution is reduced approximately by a factor of 60, (256P Vs 1P).

Application I: PSI 590MeV Ring

Accelerating orbit and tune diagram

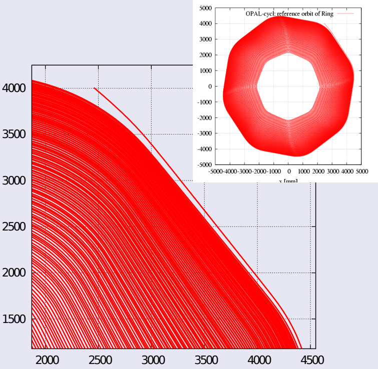


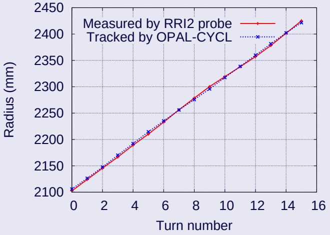


Tune calculation result is agree with FIXPO code very well!

Application I: PSI 590MeV Ring

Simulation and measurement



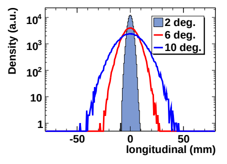


Beam center position difference is less than +/- 5 mm.

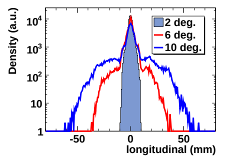
Application I: PSI 590MeV Ring

Single bunch with space charge

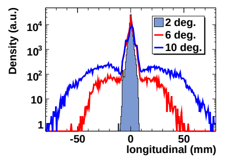
Compare different initial phase widths of 3mA beam



Turn 0



Turn 50



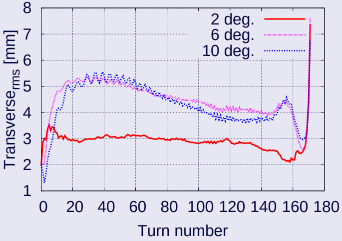
Turn 150

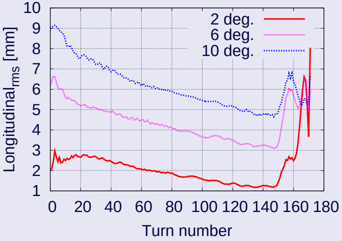
- 2^o: Keep compact shape, no tails exist
- 6^o: With tails about 3 cm long
- 10^o: With long tails of more than 6 cm long

Application I: PSI 590MeV Ring

Single bunch with space charge

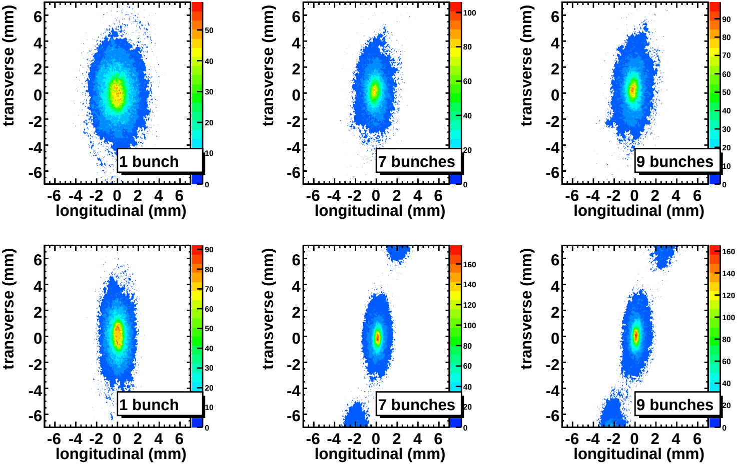
Start-to-end RMS sizes comparison of 3MeV beam





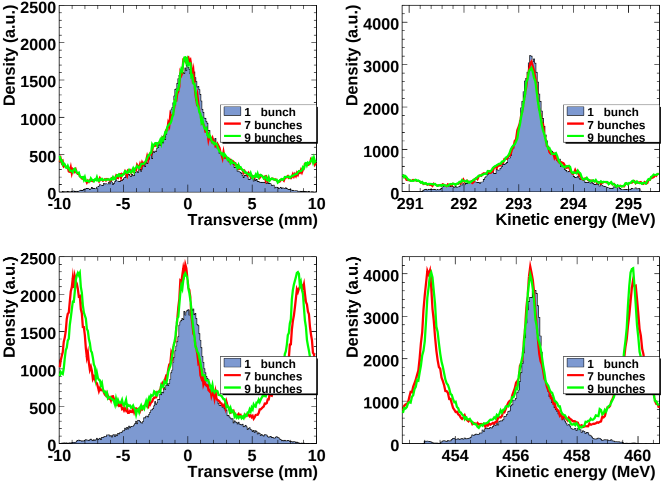
Application I: PSI 590MeV Ring

Single bunch and multiple bunches at turn 80 and 130



Application I: PSI 590MeV Ring

Single bunch and multiple bunches at turn 80 and 130



Application I: PSI 590MeV Ring

Single bunch and multiple bunches at turn 80 and 130

Animation movie

Animation for 9 bunches injection and tracking

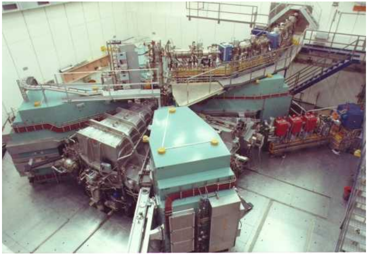
Conclusion of neighboring bunch effects of 1mA beam

- 9 bunches is enough to give out precise solution
- It has visible impacts on beam dynamics
- It makes the bunch more compact in transverse direction

Application II: PSI Injector II

3 MeV coasting beam

Animations of Beam development in 40 turns:
[0mA beam animation]
[1mA beam animation]
[3mA beam animation]

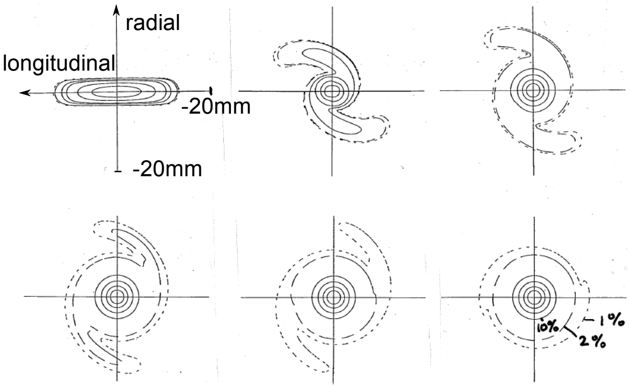


Conclusion

In Injector2, space charge effects help to develop a very compact stable core in the first several turns for more than 1mA beam.

Application II: PSI Injector II

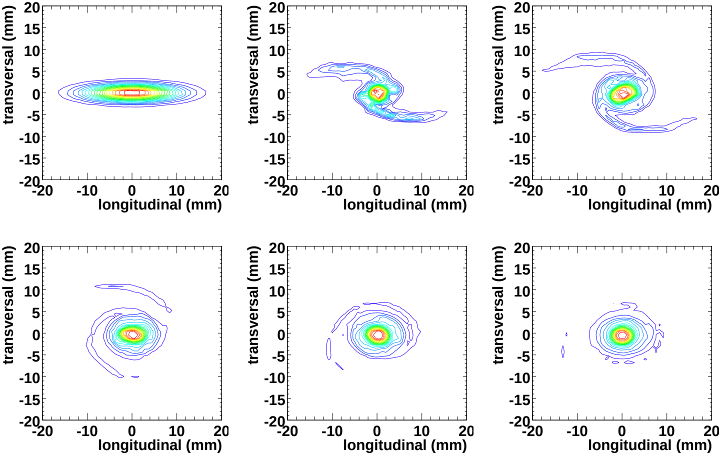
3 MeV coasting beam



I=1mA. Up: turn 0, 5, 10. Down: turn 20, 30, 40 by PICS (courtesy by S. Adam)

Application II: PSI Injector II

3 MeV coasting beam



I=1mA.Up: turn 0, 5, 10. Down: turn 20, 30, 40 by OPAL-CYCL

Outline

Conclusions

1. Establish a physical model which covers neighboring bunch effects self consistently
2. Develop a 3D parallel PIC code OPAL-CYCL , as a flavor of OPAL
3. Perform the first parallel simulation of multiple bunches in cyclotron
4. Study neighboring bunch effects on the beam's evolution quantitatively on PSI Ring cyclotron

Outline

Acknowledgments

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Thanks for your attention!