Modeling High Intensity Beams in Cyclotrons

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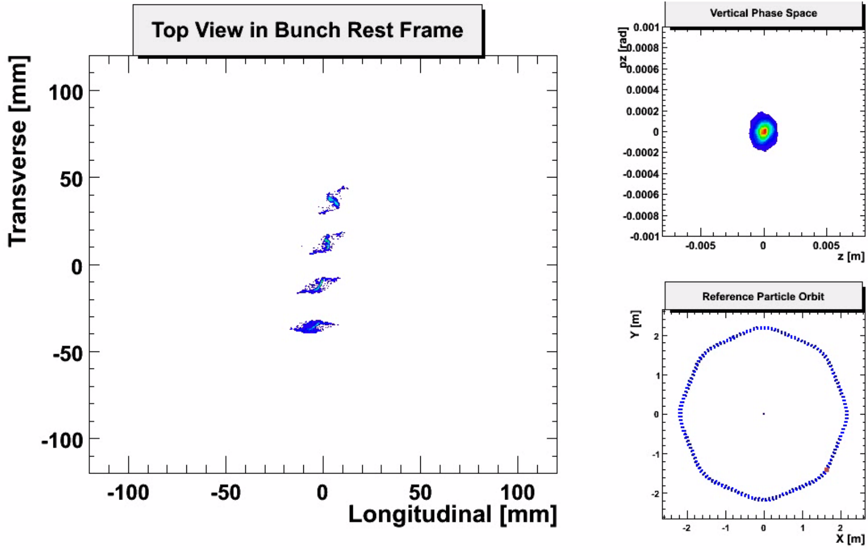
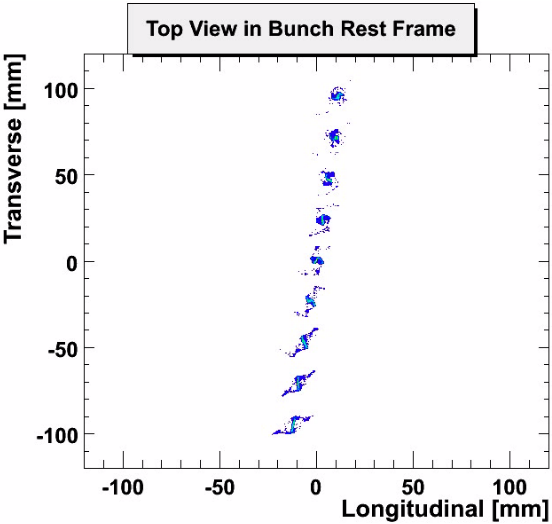
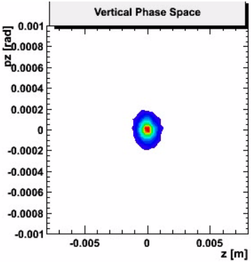
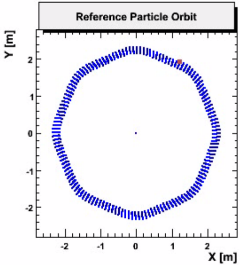

Top View in Bunch Rest Frame
Transverse [mm]
Longitudinal [mm]
100
50
0
-50
-100
-100
-50
0
50
100
Vertical Phase Space
pz [rad]
z [m]
0.001
0.0008
0.0006
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-0.0008
-0.001
-0.005
0
0.005
Reference Particle Orbit
Y [m]
X [m]
2
1
0
-1
-2
-2
-1
0
1
2


Top View in Bunch Rest Frame
Transverse [mm]
Longitudinal [mm]
100
50
0
-50
-100


Vertical Phase Space
pz [rad]
z [m]
-0.005
0
0.005


Reference Particle Orbit
Y [m]
X [m]

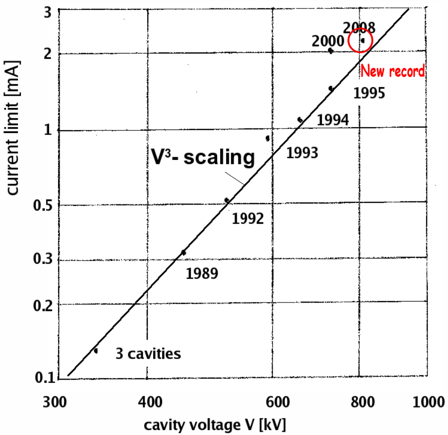
Outline

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: Space charge studies in Cyclotrons

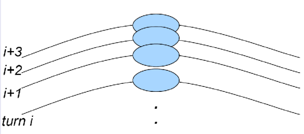
Analytic Models

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

Numerical solution

- 2D serial P-M codes: PICS, PICN by S.Adam and S. Koscielniak (1990s)
- 3D Parallel P-M codes: LIONS SP by P.Bertrand (2000s) & MAD9P by A.Adelmann (2001)

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

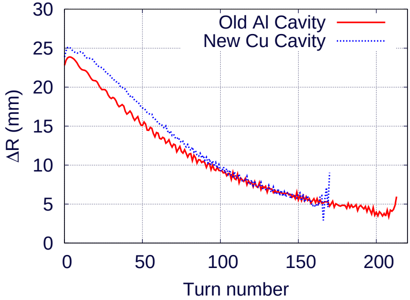


Motivation:Upgrade Project of PSI Cyclotron Facility

590 MeV Ring (CW)

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

Motivation: Upgrade Project of PSI Cyclotron Facility

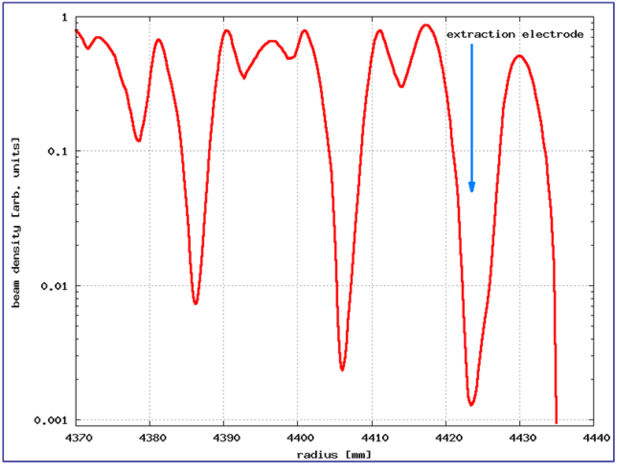


After upgrade

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

$\Rightarrow$ Neighboring bunch effects will increase!

Motivation: Understanding radial density profiles

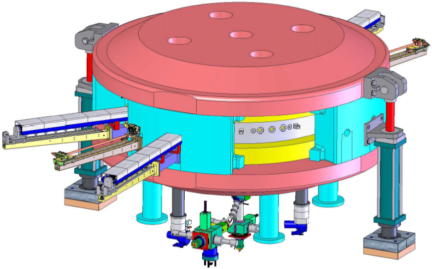


courtesy of M. Sidel (PSI)

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,
  $\Delta R_{n,n+1} = 1.5$mm
  Far smaller than beam size, multi-bunches will overlap



Outline

1. Background & Motivation
2. OPAL-CYCL : Physical Model and Algorithm
   - 3D Parallel Space Charge Solver
   - Modeling Neighboring bunch effects
3. Validations and Applications
4. Conclusions & Outlook

Introduction to OPAL-CYCL

- OPAL is a tool for charged-particle optics in large accelerator structures and beam lines including 3D space charge
- Flavours: OPAL-CYCL , OPAL-T and OPAL-MAP
- OPAL is built from the ground up as a parallel application exemplifying the fact that HPC (High Performance Computing) is the third leg of science, complementing theory and the experiment

- OPAL-CYCL is a 3D parallel P-M code for cyclotrons
- Solve Poisson equation with spectral methods
- Track in global Cartesian coordinates using RK-4 as time integrator
- Store (phase space) data in the parallel H5Part format
- Has three working modes:
  1. Tune calculation mode (single particle tracking)
  2. Single bunch tracking mode including 3D space charge
  3. Multiple bunch tracking mode including 3D space charge

Equations of Motion

Equations of motion of single charged particle in electromagnetic field:

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

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

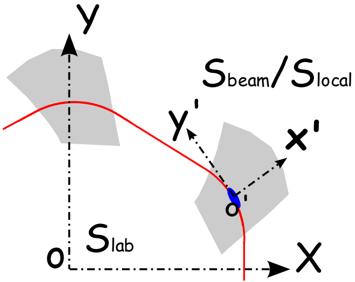
$$\mathbf{B} = \mathbf{B}_{\mathrm{ext}} + \mathbf{B}_{\mathrm{self}}.$$

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

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

The Coordinates Frames



3 frames

- $\mathbf{S}_{\mathrm{lab}}$: 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) method in a co-moving frame.

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

Algorithm 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 $\mathbf{S}_{\mathrm{lab}}$

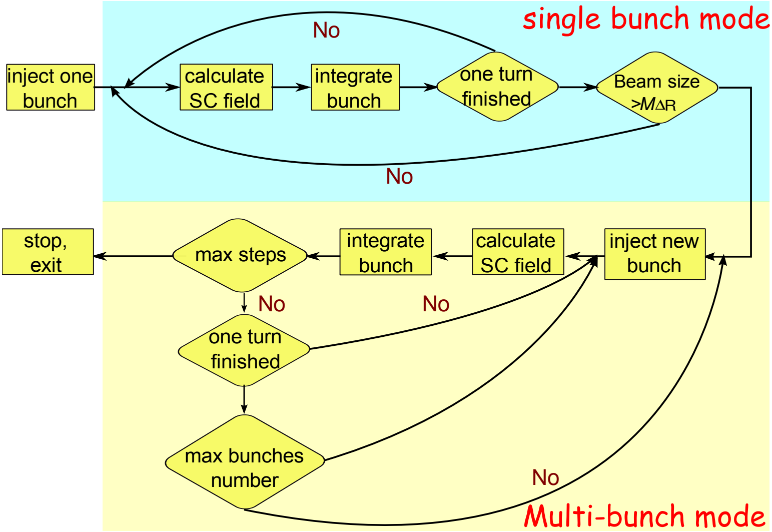
Neighboring Bunch Effects: Multi-bunch model

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

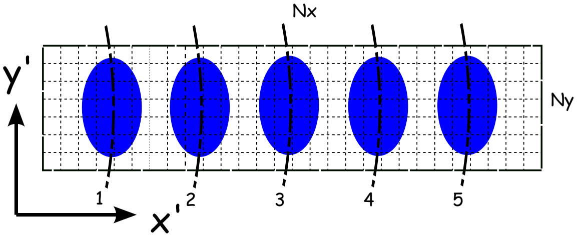
- First stage, big $\Delta R \Rightarrow$ single bunch tracking
- Second stage, small $\Delta R \Rightarrow$ multiple bunches tracking

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

Neighboring Bunch Effects: Algorithm



Neighboring Bunch Effects: Algorithm



Energy bins

- One energy bin for each bunch
- All particles grouped into bins
- For all n-bins compute space charge in the correct frame
- Rebin when energy spread exceeds a given threshold value

Outline

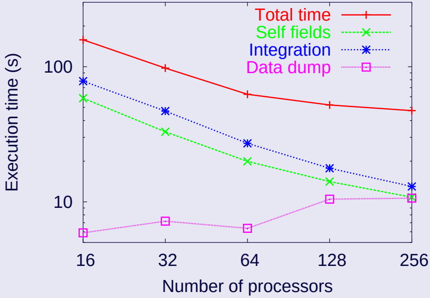
Parallel Scalability: On a Cray XT3 at CSCS, Switzerland

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

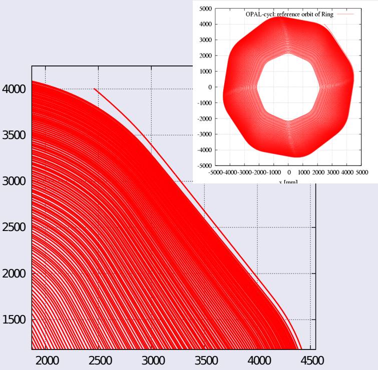
- The code scales well
- Good load-balancing
- Dumping time increased



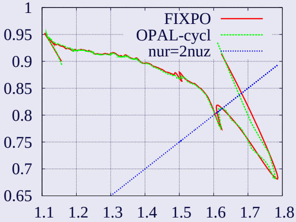
Time to solution is reduced approximately by a factor of 60,(256P Vs 1P).

Applications: PSI 590MeV Ring

Accelerating orbit and tune diagram



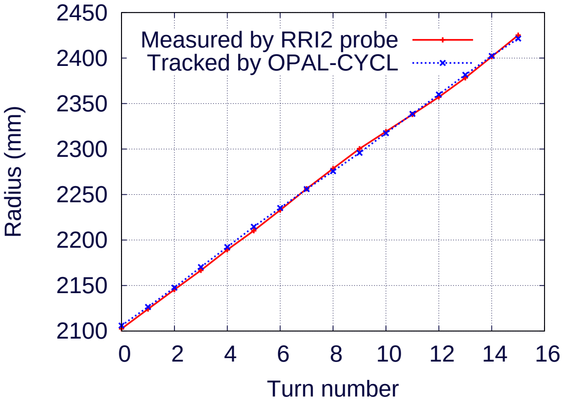
Extraction @ 590 MeV



Tune calculation result is agree with FIXPO code very well!

Applications: PSI 590MeV Ring

Simulation and measurement

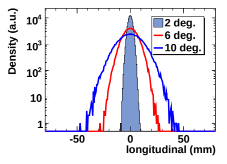


Beam center position difference is less than +/- 5 mm.

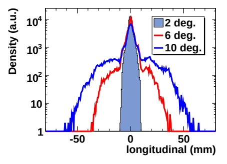
Applications: PSI 590MeV Ring

Single bunch with space charge

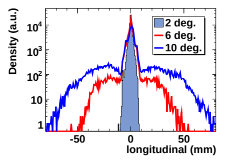
Compare different initial phase widths of 3 mA beam



Turn 0



Turn 50



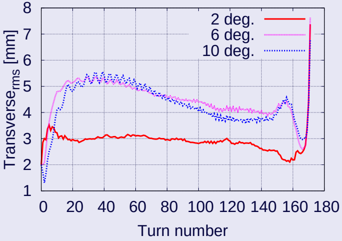
Turn 150

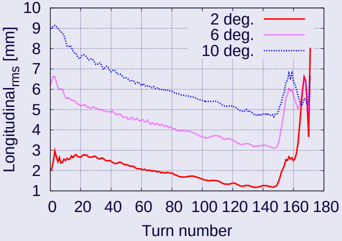
- 2^o: Keep compact shape, no tails exist
- 6^o: With tails about 3 cm long
- 10^o: With long tails of more than 6 cm long

Applications: PSI 590MeV Ring

Single bunch with space charge

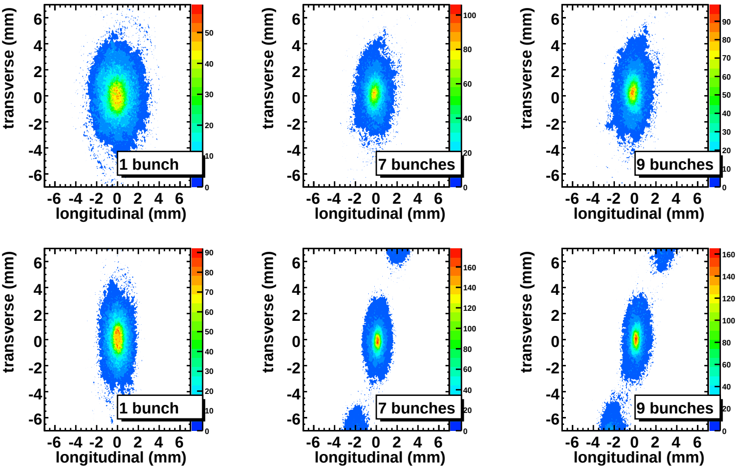
Start-to-end RMS sizes comparison of 3 mA beam





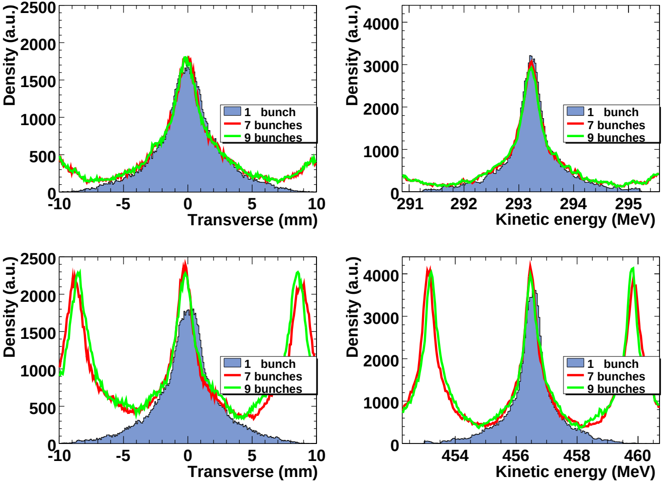
Applications: PSI 590MeV Ring

Single bunch and multiple bunches at turn 80 and 130



Applications: PSI 590MeV Ring

Single bunch and multiple bunches at turn 80 and 130



(Neighboring bunch effects of 1mA beam)

Outline

Conclusions & Outlook

- We developed a 3D parallel P-M code OPAL-CYCL
- The model includes for the first time neighboring bunch effects self consistently in a S-E simulation of the PSI-Ring Cyclotron
- Quantitative studies of neighboring bunch effects for the PSI Ring cyclotron are presented:
  - 9 bunches for converging solution
  - It has visible impacts on beam dynamics

- In 2009 we plan an extensive BD-studies to
  1. obtain proper initial conditions for the Ring Cyclotron
  2. match mesured profiles with simulations in the Ring Cyclotron
- Add collimation in OPAL-CYCL

Acknowledgments

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