

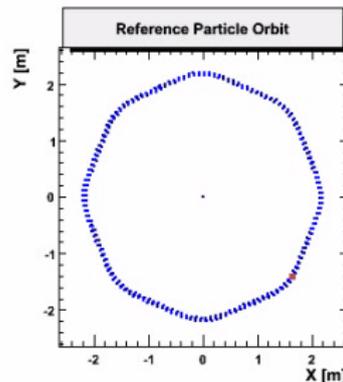
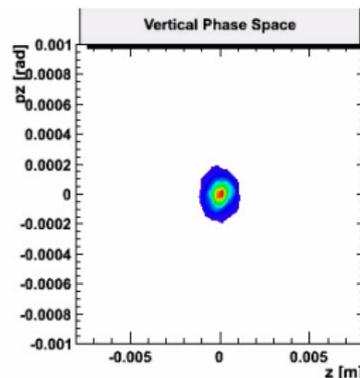
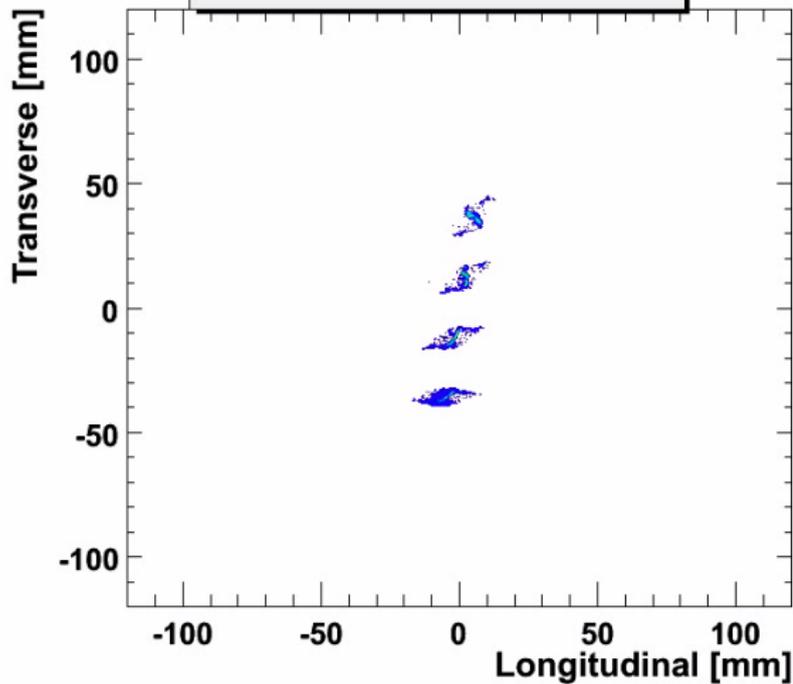
Modeling High Intensity Beams in Cyclotrons

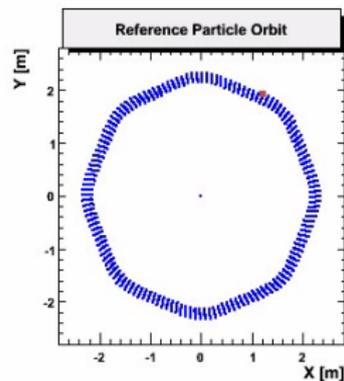
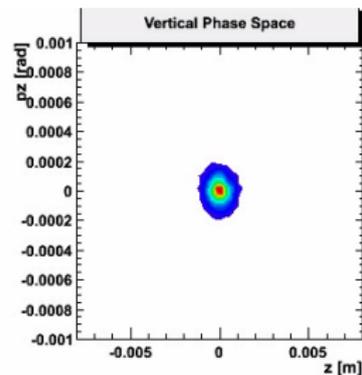
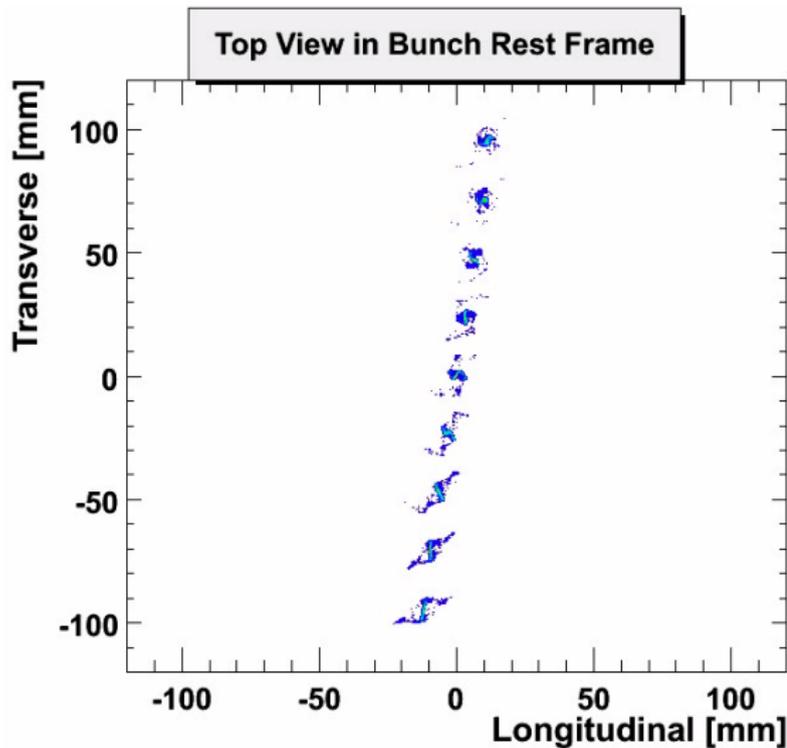
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August 28, 2008

For more information visit <http://amas.web.psi.ch/>

Top View in Bunch Rest Frame





Outline

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

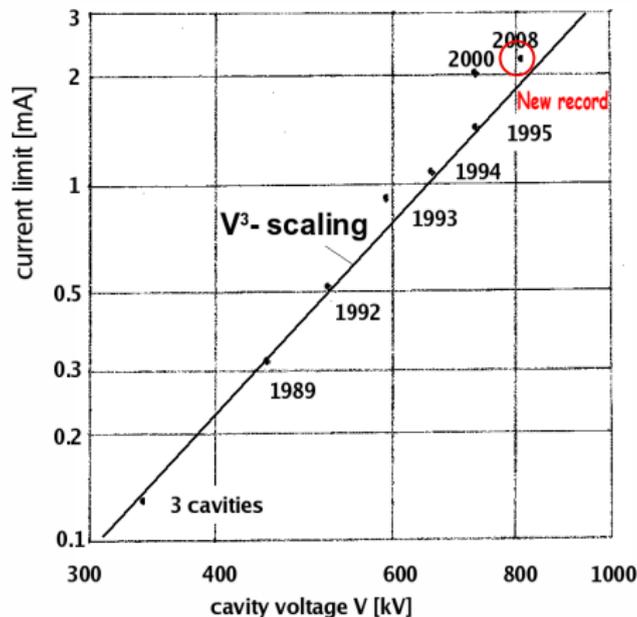
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Background: History

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

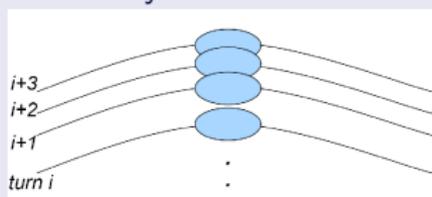
Analytic Models

- 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 \Rightarrow Not much work has been done yet.
E.Pozdeyev introduced “auxiliary bunch” in his serial code CYCO (2003).



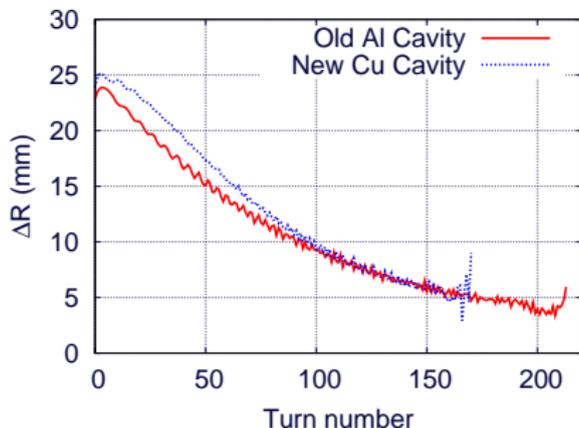
Motivation: Upgrade Project of PSI Cyclotron Facility

590 MeV Ring (CW)

- Beam Current/Power:
 $2\text{mA}/1.2\text{MW} \Rightarrow 3\text{ mA}/1.8\text{MW}$
The **highest beam power cyclotron** in the world
- Turns number:
 $200 \Rightarrow$ less than 160
- Larger turn separation after upgrade



Motivation: Upgrade Project of PSI Cyclotron Facility

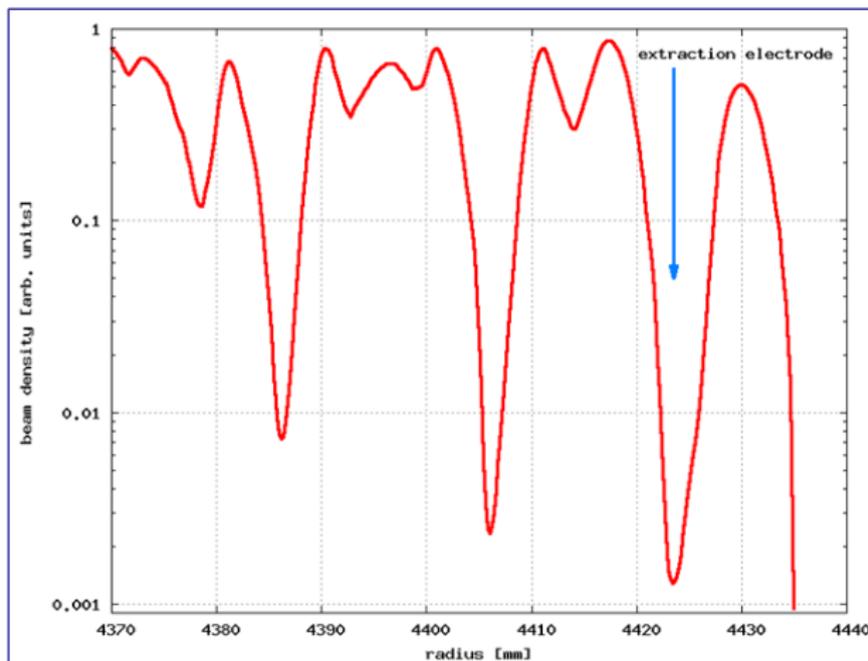


After upgrade

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

⇒ Neighboring bunch effects will increase!

Motivation: Understanding radial density profiles

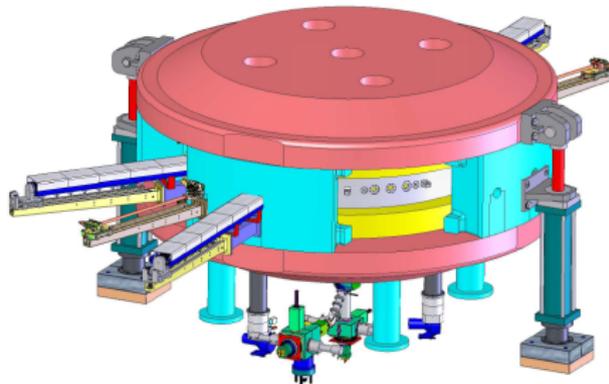


courtesy of M. Sidel (PSI)

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



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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:

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

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

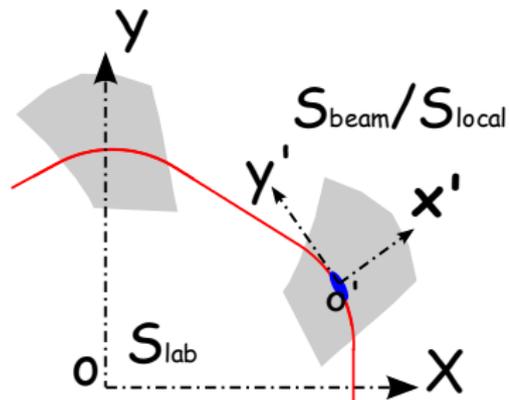
$$\mathbf{B} = \mathbf{B}_{\text{ext}} + \mathbf{B}_{\text{self}}.$$

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

The Coordinates Frames



3 frames

- S_{lab} : The global lab frame
- S_{local} : The local instantaneous frame
- S_{beam} : The beam rest frame

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

Space charge fields can be obtained 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}_{beam}
- ▷ Use FFT on ρ^D and G^D to obtain $\hat{\rho}^D$ and \hat{G}^D
- ▷ Determine $\hat{\phi}^D$ on the grid using $\hat{\phi}^D = \hat{\rho}^D \cdot \hat{G}^D$
- ▷ Use inverse FFT on $\hat{\phi}^D$ 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}_{sc} and \mathbf{B}_{sc} in \mathbf{S}_{lab}

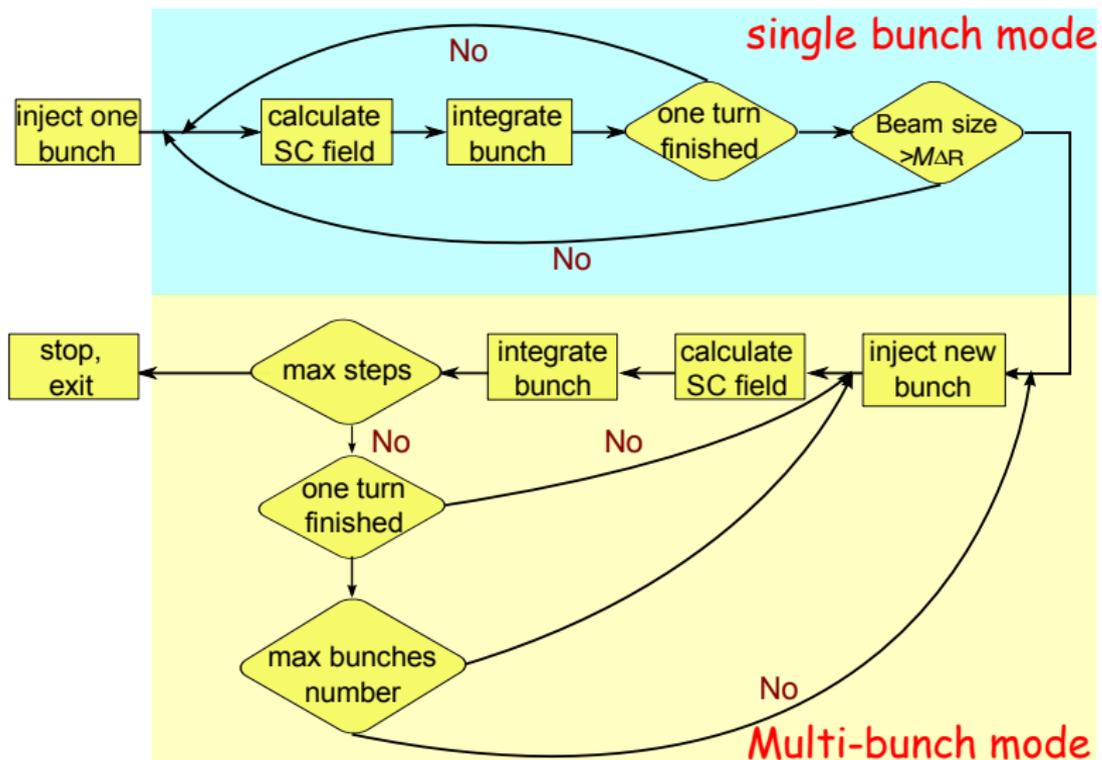
Neighboring Bunch Effects: Multi-bunch model

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

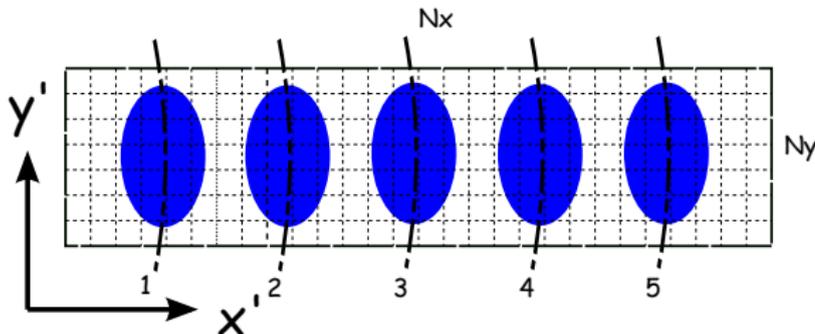
- First stage, big $\Delta R \Rightarrow$ single bunch tracking
- Second stage, small $\Delta R \Rightarrow$ multiple bunches tracking

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

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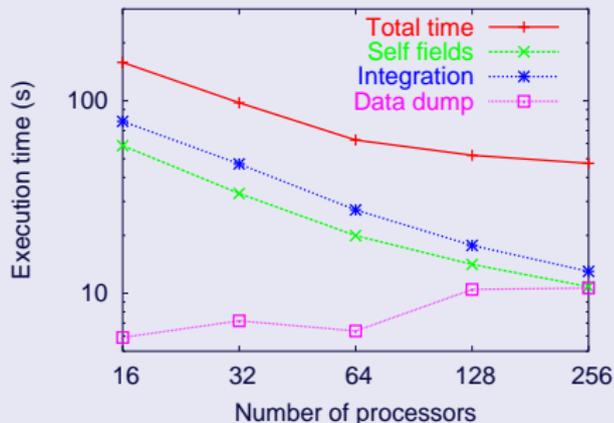
Parallel Scalability: On a Cray XT3 at CSCS, Switzerland

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

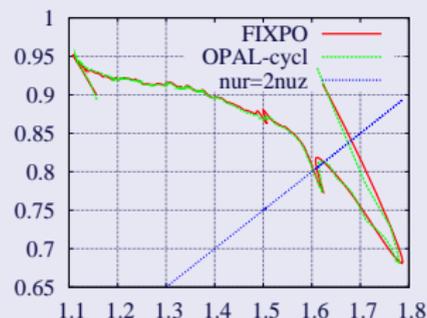
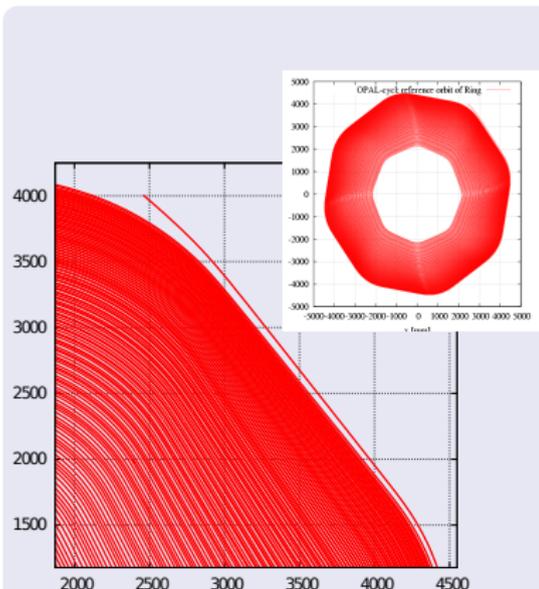
- The code scales well
- Good load-balancing
- Dumping time increased



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

Applications: PSI 590MeV Ring

Accelerating orbit and tune diagram

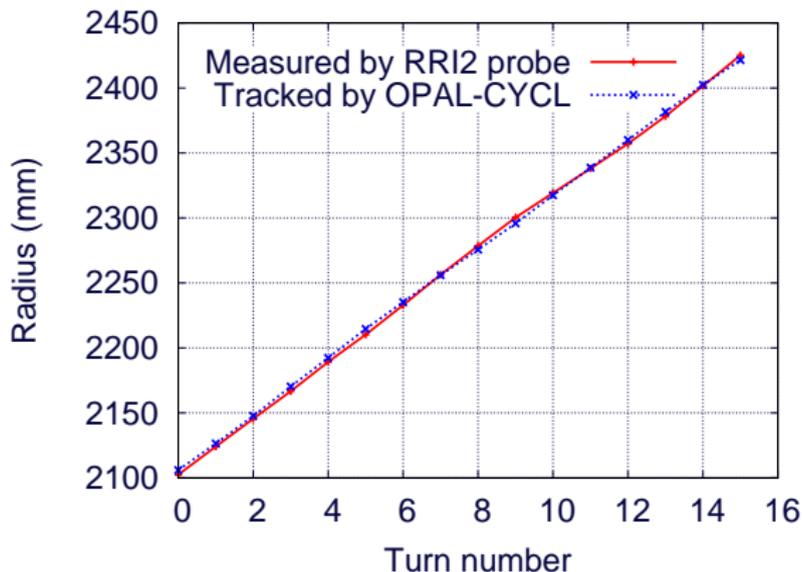


Tune calculation result is agree with FIXPO code very well!

Extraction @ 590 MeV

Applications: PSI 590MeV Ring

Simulation and measurement

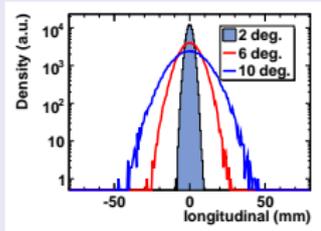


Beam center position difference is less than ± 5 mm.

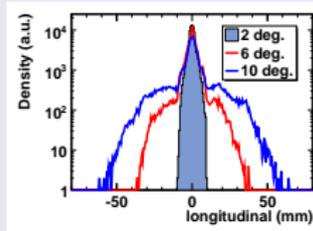
Applications: PSI 590MeV Ring

Single bunch with space charge

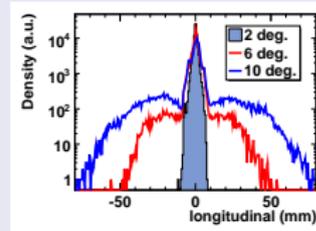
Compare different initial phase widths of 3 mA beam



Turn 0



Turn 50



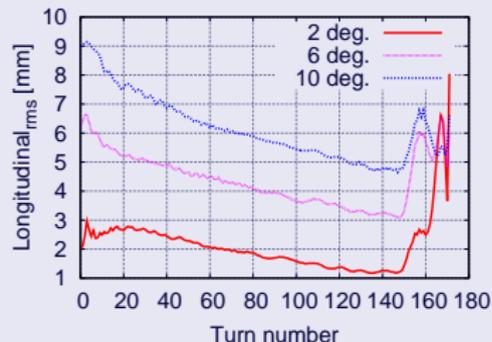
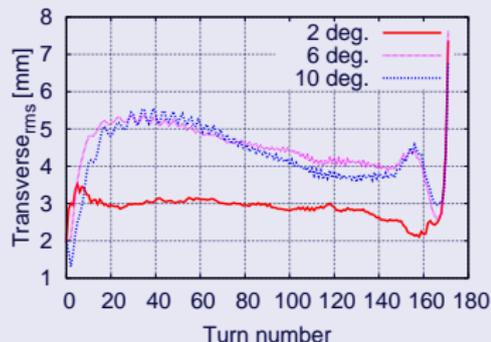
Turn 150

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

Applications: PSI 590MeV Ring

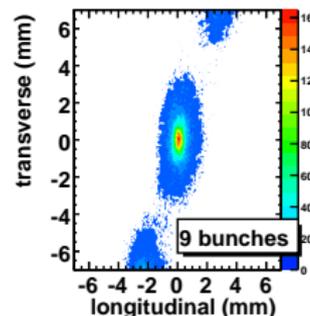
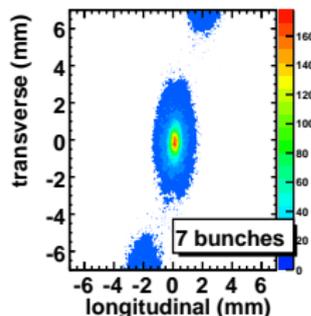
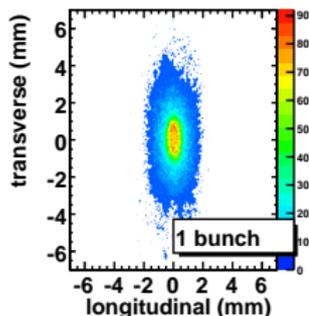
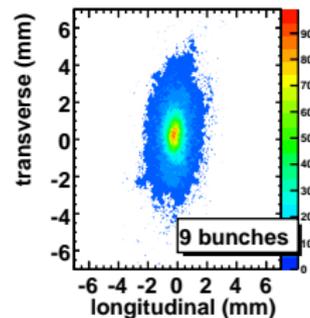
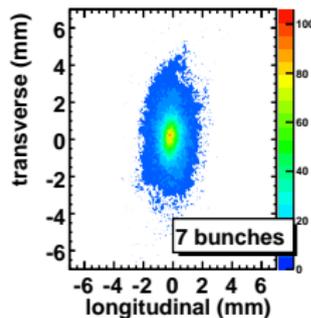
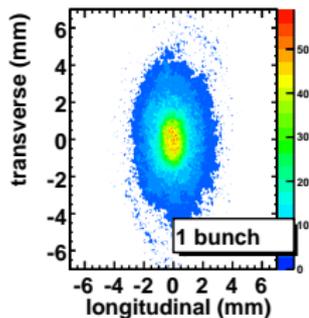
Single bunch with space charge

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



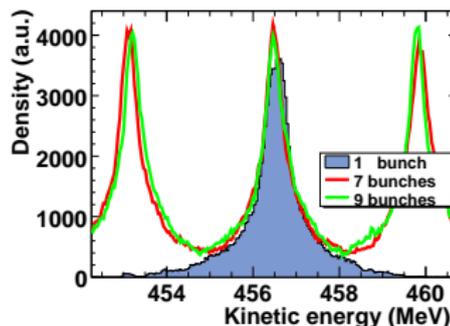
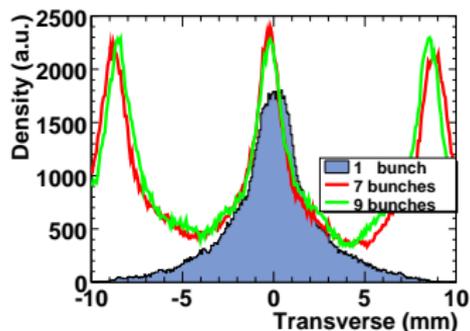
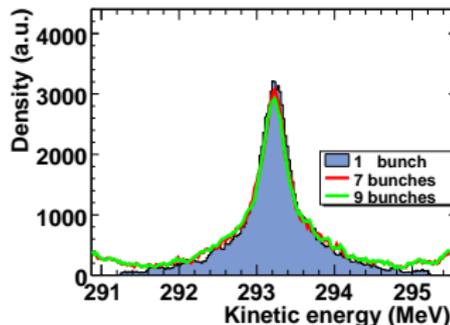
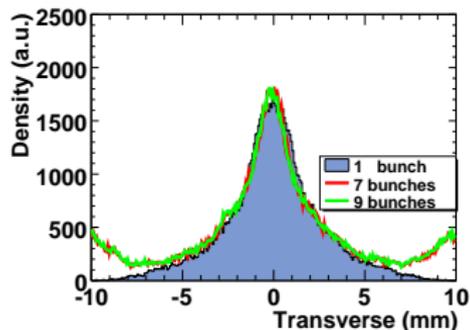
Applications: PSI 590MeV Ring

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)

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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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