Space Charge Simulation on High Intensity Cyclotrons:

Code Development and Applications

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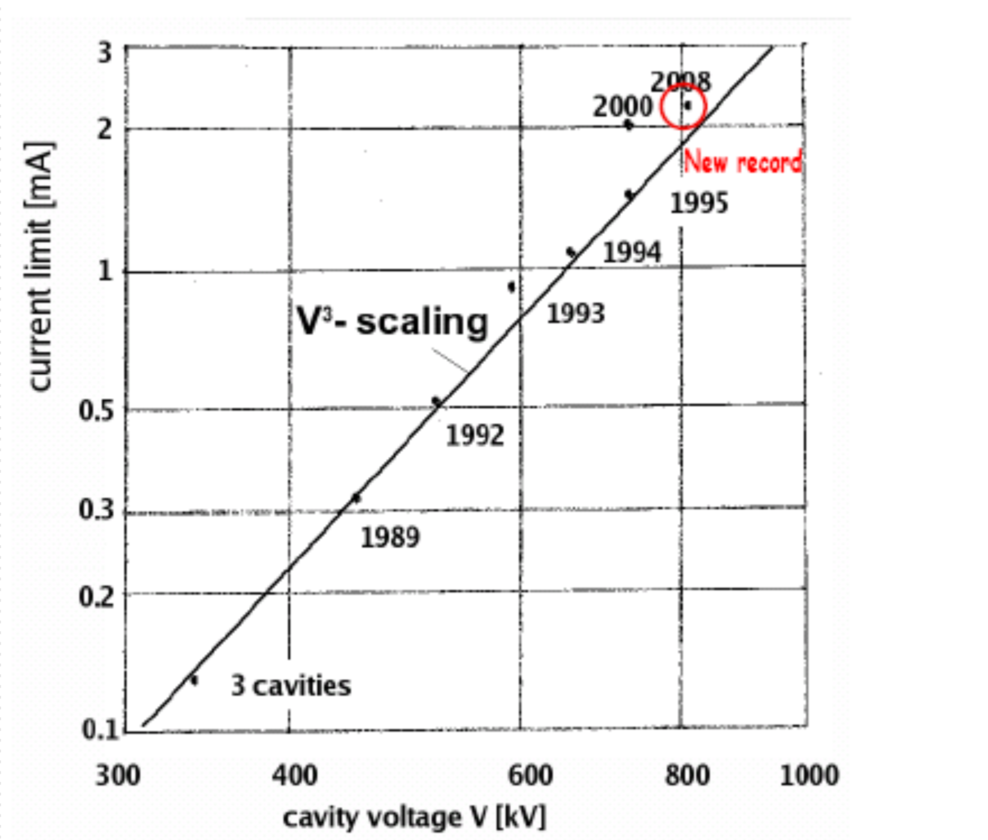
Background: History

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 PSI Ring cyclotron (courtesy by W.Joho, 1981)

Background: Brief review of space charge studies

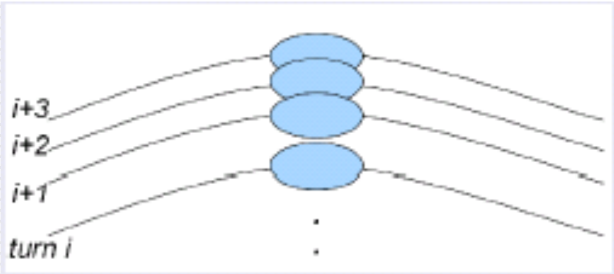
Analytic Models

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

Numerical Solution

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

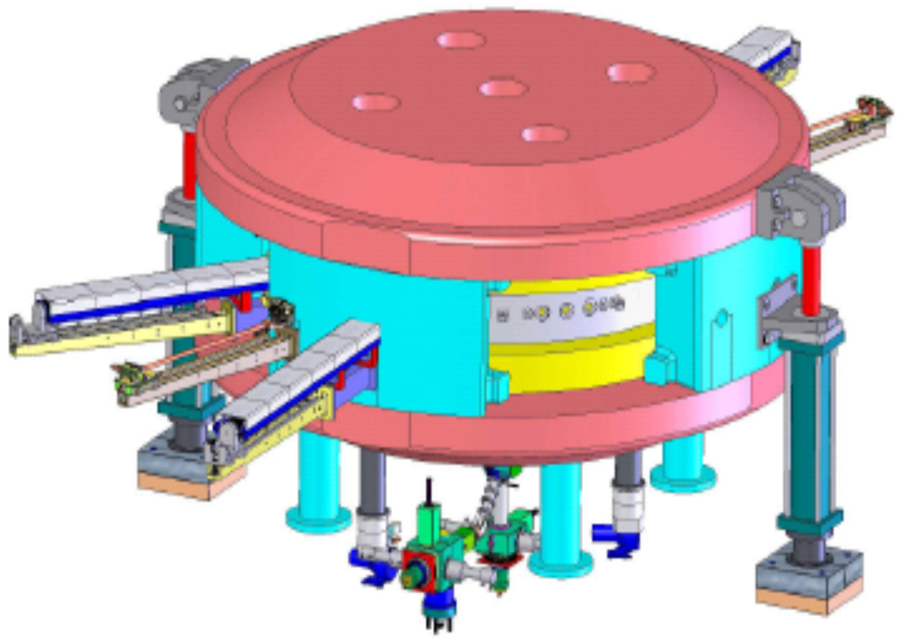
Neighboring bunch effects → Not much work has been done yet. E. Pozdeyev introduced "auxiliary bunch" in his serial code CYCO(2003)



Motivation: Compact Cyclotron under Constrution at CIAE

100MeV H- Cyclotron CYCIAE-100

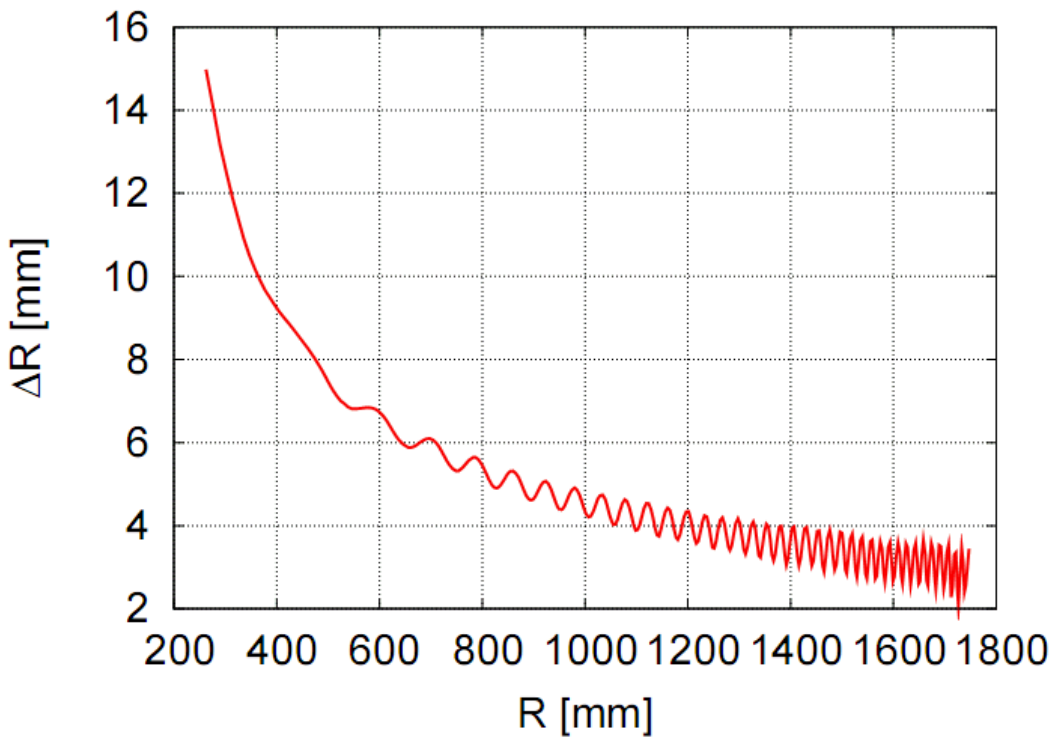
- Designed beam current 0.2mA, future 0.5mA
- Injection energy is 40keV
- Turns number is about 310
- Energy gain per turn is about 0.4MeV @ extraction
- Multi-turn extraction by stripper @ radius of 1.9m



Motivation: Compact Cyclotron under Constrution at CIAE

- Turn separation ΔR is less than 6mm at the main acceleration region.

- At extraction point, ΔR=3mm. Smaller than beam size, multi-bunches will overlap.



Characteristics of OPAL-CYCL

- 3D parallel PIC code for cyclotrons and FFAGs
- Based on several other framework (IPPL, CLASSIC, H5Part, HDF5)
- Use time as independent variable
- Solve Poisson equation with FFT methods and energy bin 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:

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

$$E = E_{ext} + E_{self}$$

$$B = B_{ext} + B_{self}$$

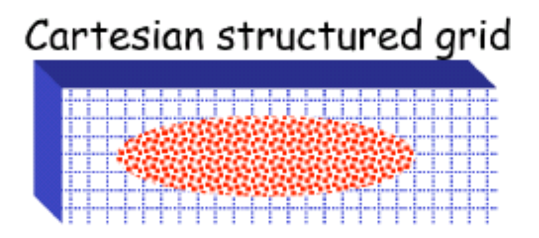
E_{ext}, B_{ext} ← measured field map or commercial software

E_{self}, B_{self} ← solve Poisson equation

- Two assumptions are valid for cyclotrons
  - Wake field & image charge effects are smaller than space charge
  - Particles relative motion in a bunch is non-relativistic

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 $\vec{k} = (l, n, m)$

$$\nabla^2 \phi^D(\vec{k}) = -\frac{\rho^D(\vec{k})}{\varepsilon_0}, \vec{k} \in \Omega^D$$

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

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

Neighboring bunch effects: Multi-bunch model

- Multi-bunch model

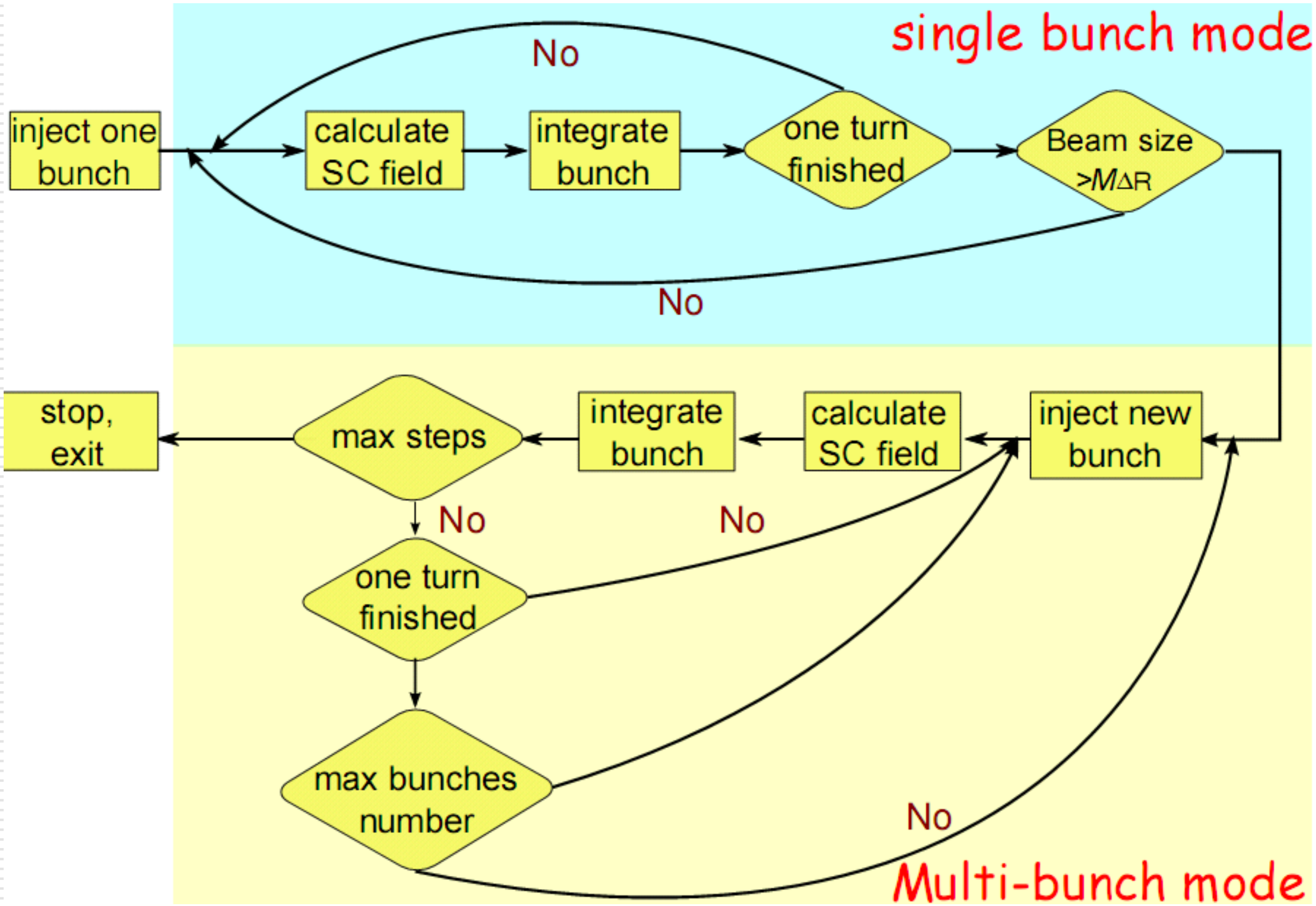
In our model, the injection-to-extraction simulation is divided into two stages:

- First stage, big ΔR=> single bunch tracking
- Second stage, small ΔR=> 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.

- Remark
  - 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: flow chart



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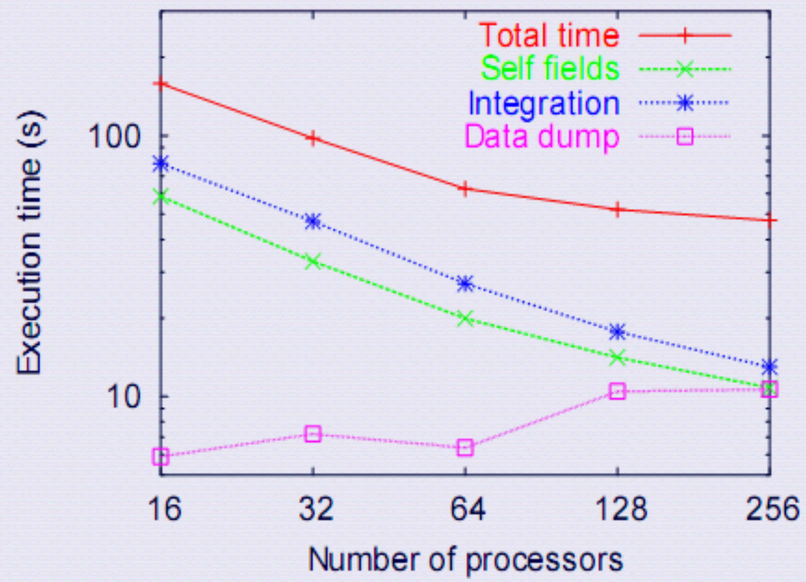
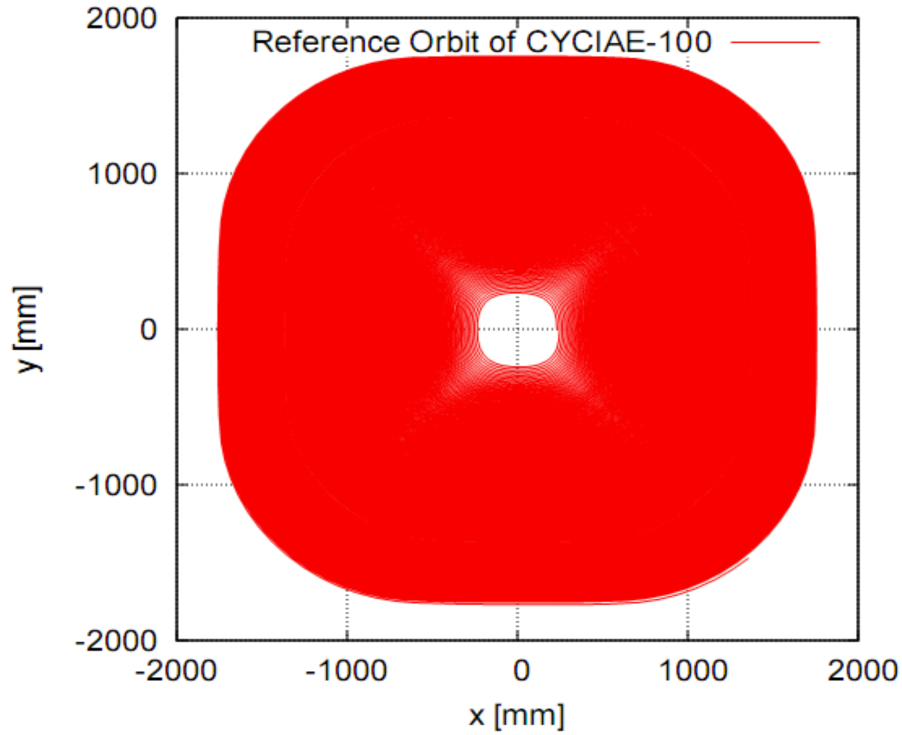
Parallel Scalability: Test on Cray XT3 at CSCS,Switzerland

- **Setup**
  - 10^6 particles
  - 3D FFT on a 64^3 grid
  - Track 200 time steps
  - Gaussian distribution
- **Observations**
  - The code scales well
  - Good load-balancing
  - Dumping time increased



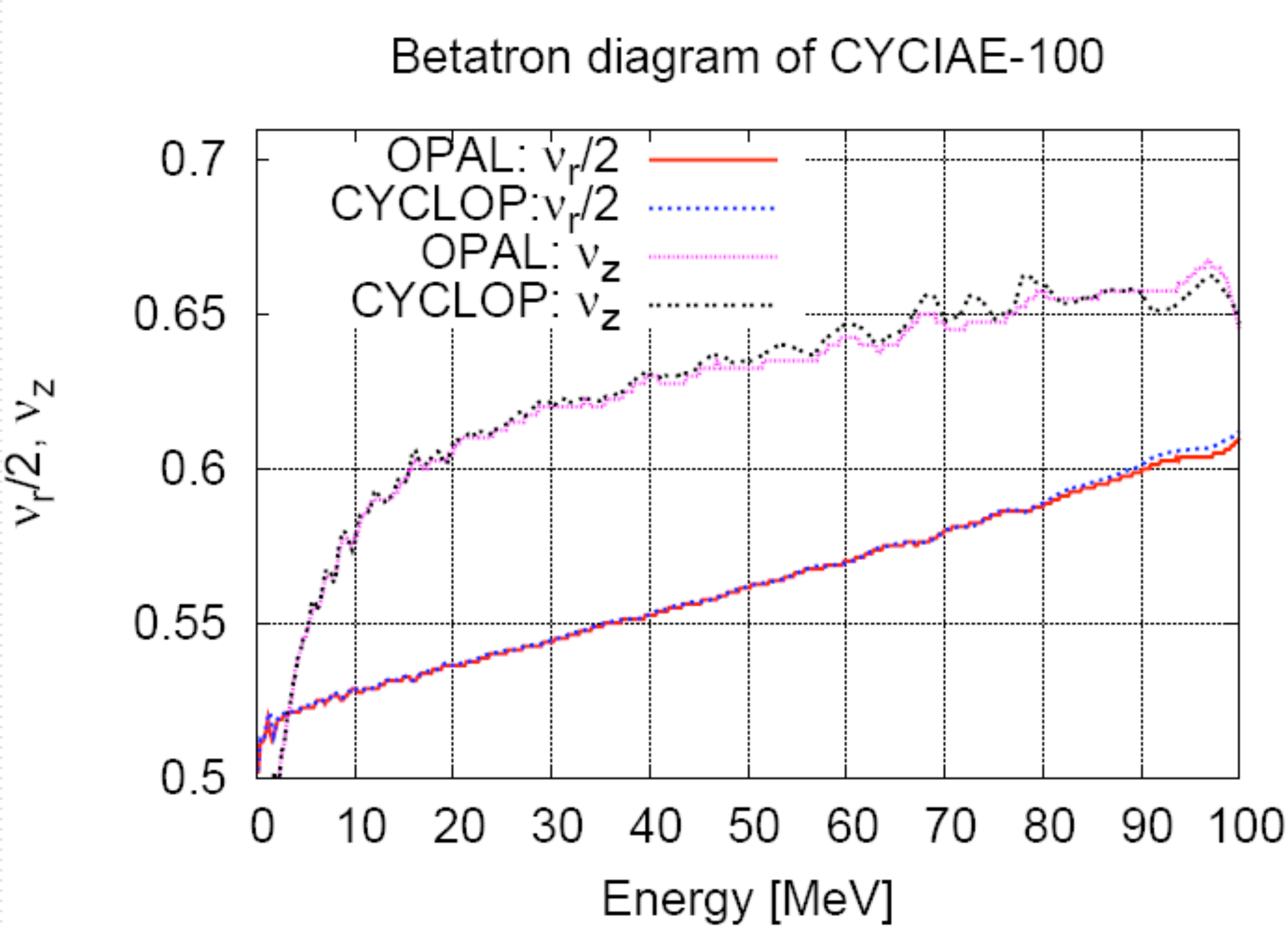
Time to solution is reduced approximately by a factor of 60, (256P Vs 1P).

Application I: AEO



Calculation of the accelerating reference orbit of CYCIAE-100

Application I : betatron tune



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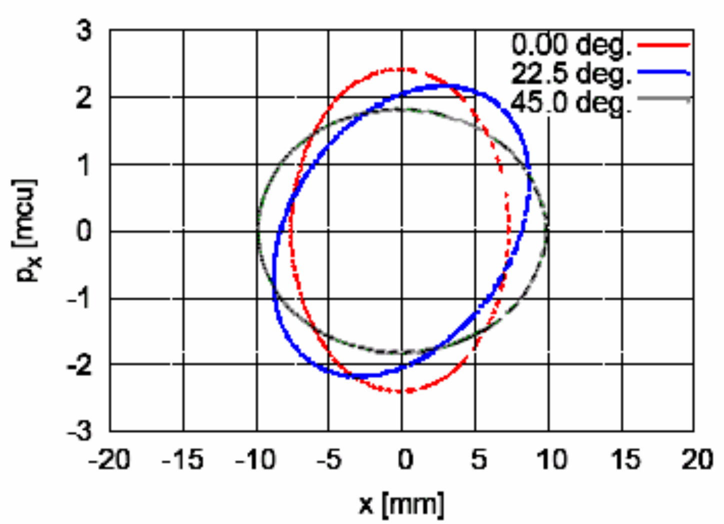
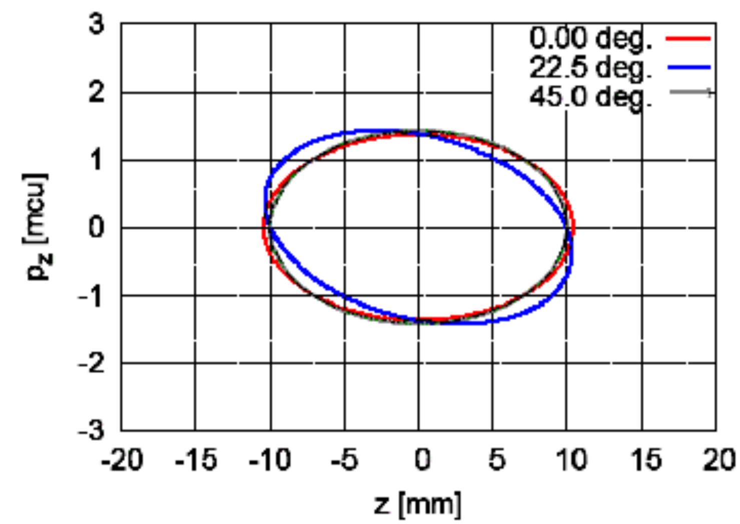
Application I : Eigen ellipse calculation

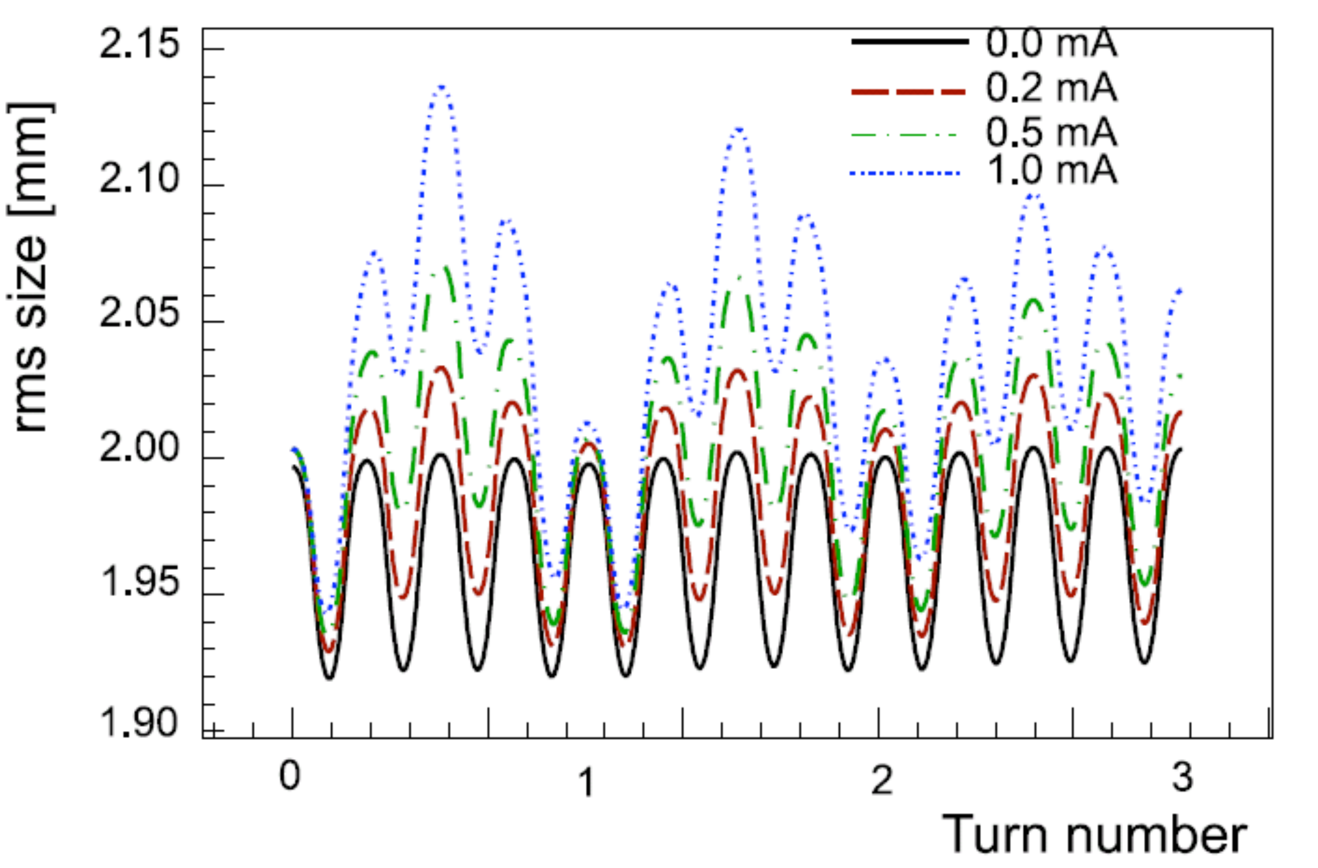




Eigen-ellipse @ 1.49MeV

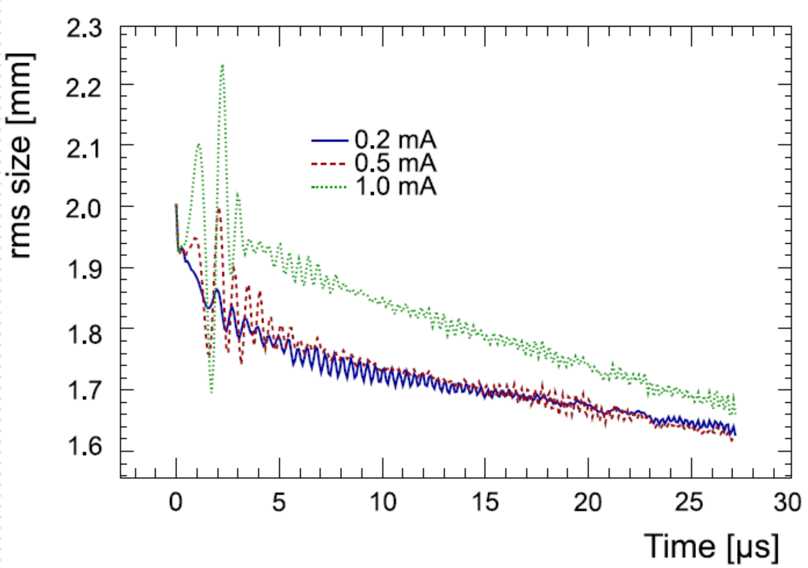
Nu_r= 1.04 Nu_z=0.45

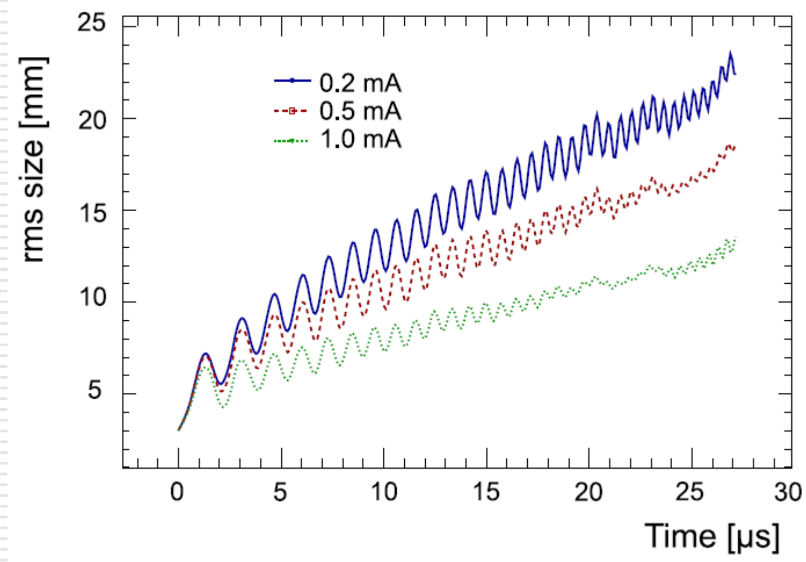
Application I : coasting beam @ 1.49MeV



Mismatching in radial direction caused by space charge

ApplicationI: single bunch from 1.49MeV to 100MeV





Axial direction

longitudinal direction

Observation:

Axial: space charge cause mismatching and enlarge the envelope

Longitudinal: vortex motion caused by space charge can reduce the phase width significantly

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Application I： neighboring bunch effects

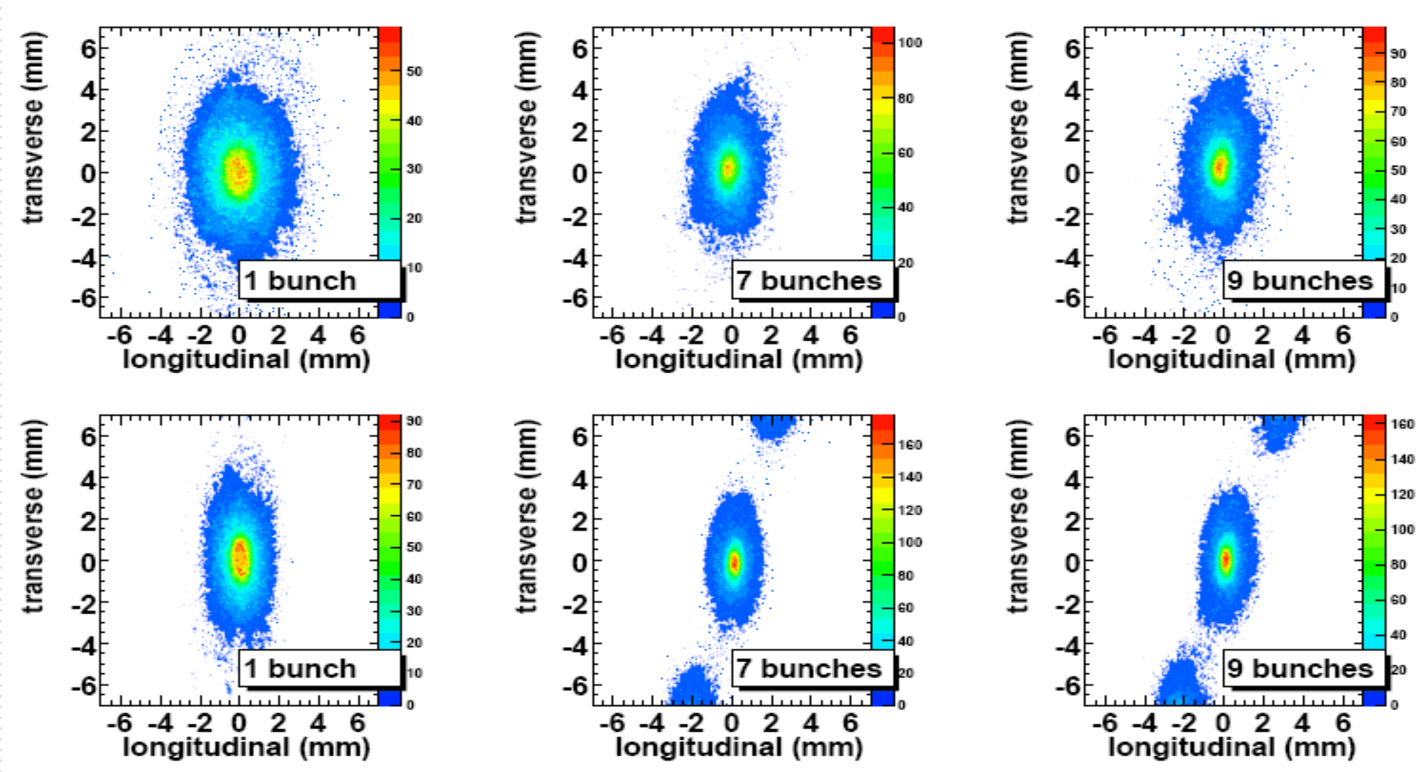
- Setup:
  - 17 bunches injected, 10^5 particles per bunch
  - $256 \times 32 \times 32$ mesh size
  - Gaussian distribution

Animation of multi-bunch injection for CYCIAE-100

Remark:

Because the multi-bunches overlap heavily at large radial area on this machine, quantitative analysis is not easy. More detail study is under going.

Application II : neighboring bunch effects



turn 80

turn 130

Conclusions:

- Establish a physical model which covers neighboring bunch effects self consistently
- Develop a 3D parallel PIC code OPAL-CYCL
- Perform the first parallel simulation of multiple bunches in compact cyclotron
- Study space charge effects on CYCIAE-100 and PSI Ring

Thank You !

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