

THE ORBIT SIMULATION CODE: BENCHMARKING AND APPLICATIONS

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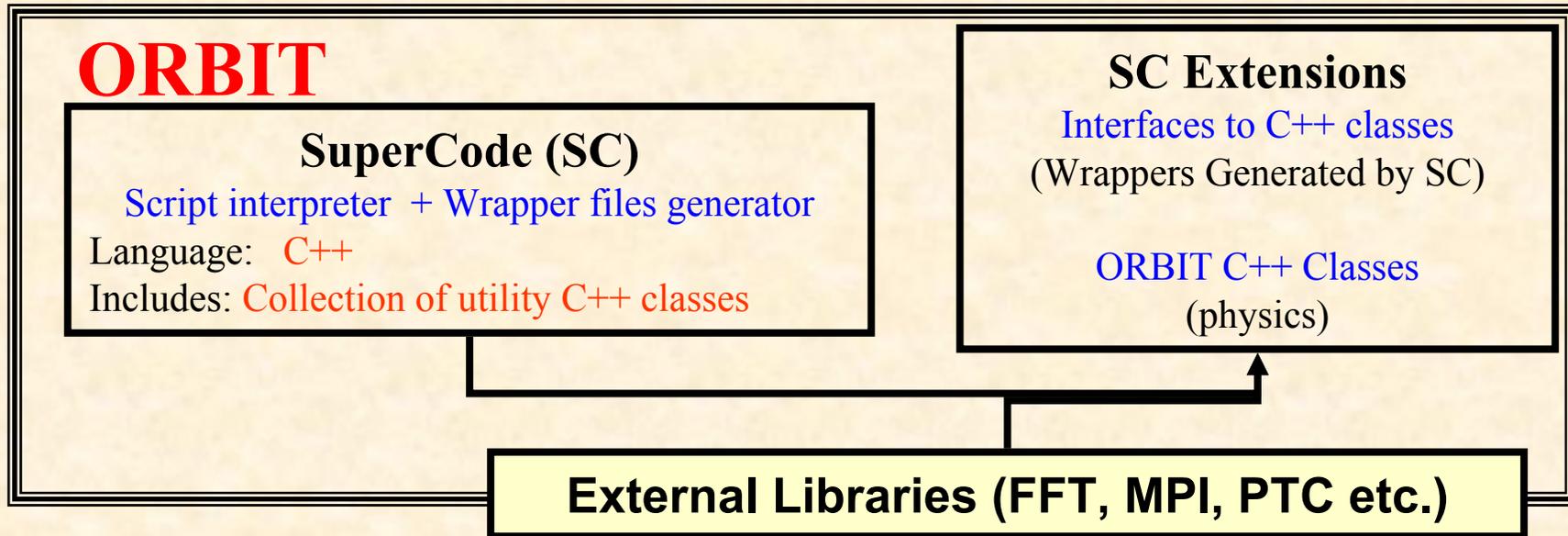
ICAP'06, October 2, 2006

ORBIT Code

ORBIT (Objective Ring Beam Injection and Transport code)

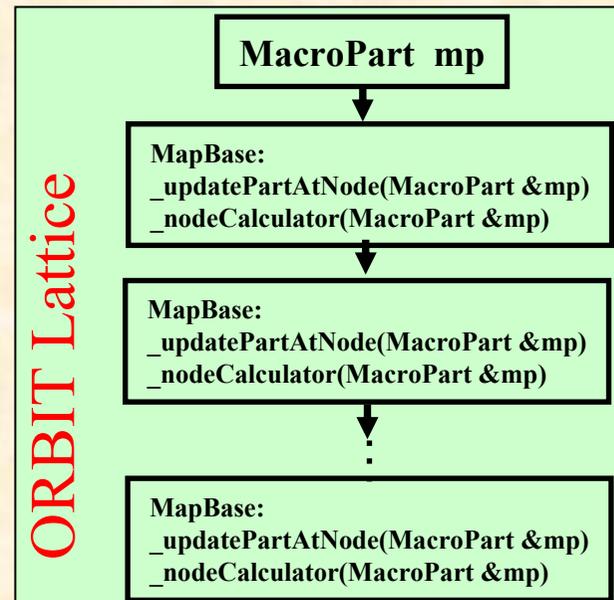
- ORBIT is an object-oriented, open-source code started at SNS for simulating high intensity rings.
- ORBIT is a particle tracking code
 - Macro-particles in 6D phase space
 - It uses s , not t , as its independent variable.
 - Uses PIC for collective effects simulations
 - Accelerator lattice is a set of Nodes
- Its purpose is the design and analysis of high intensity rings. **We also use it on beam lines when appropriate.**
- ORBIT incorporates a sizeable collection of physics, engineering, and diagnostic models.
- The emphasis in developing ORBIT has always been the incorporation of models that allow application to realistic accelerator problems.

ORBIT Programming Structure



ORBIT is a script interpreter of the extended SuperCode program language. The ORBIT program is a script to be interpreted.

- Programming language for free
- No need to compile
- Flexible, scripts are easy to create
- Can be extended further



History of ORBIT Development

- **Year 1997 - first files created by John Galambos**
 - **Year 1999 - cvs repository was created. Other developers started joining the team.**
 - **Years 1999 – 2006 - active development of collective interaction, collimation, and one-particle dynamic modules, parallel computing based on MPI.**
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The base structure of ORBIT is unchanged. Due to this structure developers are able to work practically independently. The parallel capabilities were present from the beginning, but the code was moved from PVM (outdated now) to MPI (latest wide accepted technology).

ORBIT: Inventory of Models

- ORBIT is designed to simulate real machines: it has detailed models for
 - Injection foil and painting ([Galambos, Holmes, Cousineau, Coupland](#)).
 - Single particle transport through various types of lattice elements ([Holmes, Galambos, Abrams, Michelotti, Forest, Shishlo](#)).
 - Magnet Errors, Closed Orbit Calculation, Orbit Correction ([Holmes, Bunch](#)).
 - RF and acceleration ([Galambos, Holmes](#)).
 - Longitudinal impedance and 1D longitudinal space charge ([Galambos, Beebe-Wang, Luccio](#)).
 - Transverse impedance ([Danilov, Shishlo](#)).
 - 2.5D transverse space charge with or without conducting wall beam pipe ([Holmes, Galambos](#)).
 - 3D space charge ([Danilov, Holmes](#)).
 - Feedback for Stabilization ([Danilov](#)).
 - Apertures and collimation ([Cousineau, Catalan-Lasheras](#)).
 - Electron Cloud Model ([Shishlo, Sato, Danilov, Holmes](#)).
 - **Tracking in 3D Magnetic Fields** ([Holmes, Perkett](#))
- ORBIT has an excellent suite of routines for beam diagnostics ([Holmes, Galambos](#)).

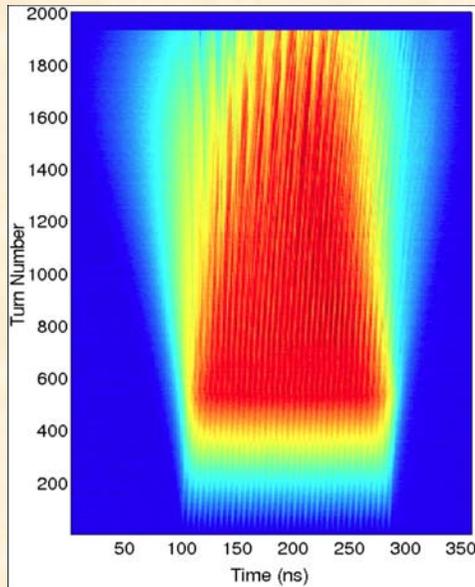
Benchmarking Techniques

- **Comparison between two computer codes.** It is very common in the case of inheritance.
- **Comparison between simulation and analytic results.** It is useful for debugging separate parts of the code, modules, and their combinations.
- **Comparison between simulation and real experimental data.** It is the most comprehensive test of models, because it usually requires the use of several modules at the same time.
 - Data from Proton Storage Ring (PSR) at the Los Alamos Neutron Science Center (LANSCE), USA are a natural source for benchmarking the ORBIT code .

Longitudinal Space Charge and Impedances (1)

- **ORBIT longitudinal impedances and/or space charge module inherits from ESME code (J. A. MacLachlan, FNAL)**
 - Impedances are represented as longitudinal kicks at localized nodes
 - Longitudinal space charge forces are combined with impedances by using FFT methods and convolution with the beam current harmonics
- **Longitudinal Space Charge and Impedance Module has been successfully benchmarked against**
 - analytic Vlasov model calculations of instability thresholds
 - results of ESME code
 - experimental data from the Los Alamos Proton Storage Ring (PSR) showing longitudinal microwave instability
 - experimental data from the Los Alamos Proton Storage Ring (PSR) showing long-lived linac micro-bunch structure during beam storage with no rf bunching (S. Cousineau, V. Danilov, and J. Holmes, R. Macek, Phys. Rev. ST Accel. Beams 7, 094201 (2004).)

Longitudinal Space Charge and Impedances (2)



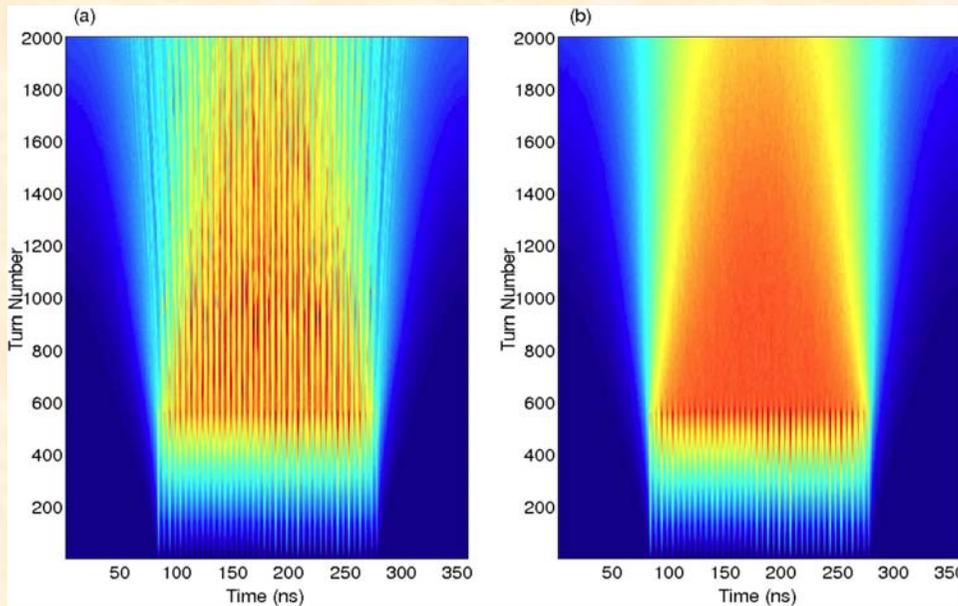
S. Cousineau, V. Danilov, and J. Holmes, R. Macek,
Space-charge-sustained micro-bunch structure in the Los Alamos Proton Storage Ring
Phys. Rev. ST Accel. Beams 7, 094201 (2004).



Experimental Data

Waterfall plot of the wall current monitor signal for the chopped beam experiment. The beam gap region is displayed in blue.

Beam injection ends at 559 turns. The high frequency variations in color indicate the micro-bunch structure of the beam



ORBIT Simulation

Left: with Longitudinal SC

Right: without

Transverse Impedance (TI) Modules

ORBIT has two independent transverse impedance modules. In both modules TI Nodes distributed along the ORBIT lattice apply transverse momentum kicks to the particles.

Frequency Domain Module

- It uses products of Fourier coefficients of the current and the impedances at corresponding frequencies to calculate the transverse kick (similar to the longitudinal impedance module approach).

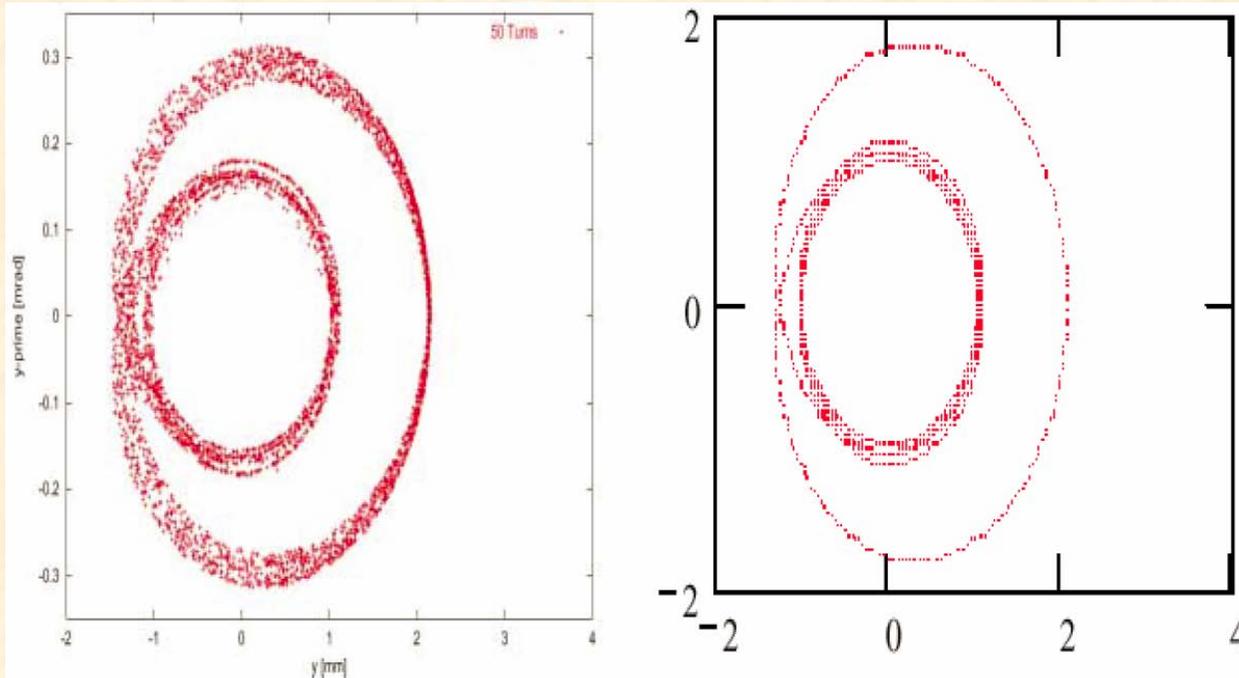
Time Domain Module

- It uses a wake field of the local element in the lattice to calculate the transverse force kick.
- The wake function should satisfy a phasor condition.

TI Frequency Domain Module Benchmark

This module was benchmarked against an exactly solvable case:
a coasting beam with Lorentz energy distribution in a constant focusing storage ring
with a single harmonic transverse impedance.

The lattice has constant beta function, impedance is included only for vertical motion (for the case shown it is equal to 1 MOhm/m). The total length of the ring is 248 meters, the frequencies are 6.4 (horizontal) and 6.3 (vertical), the number of protons is equal to 10^{14} . In the simulation only particles with up to 10 Lorentz tune spreads were considered. The kinetic energy is 1 GeV, and the Lorentz energy spread is 10 MeV.



Phase space after 50 turns.

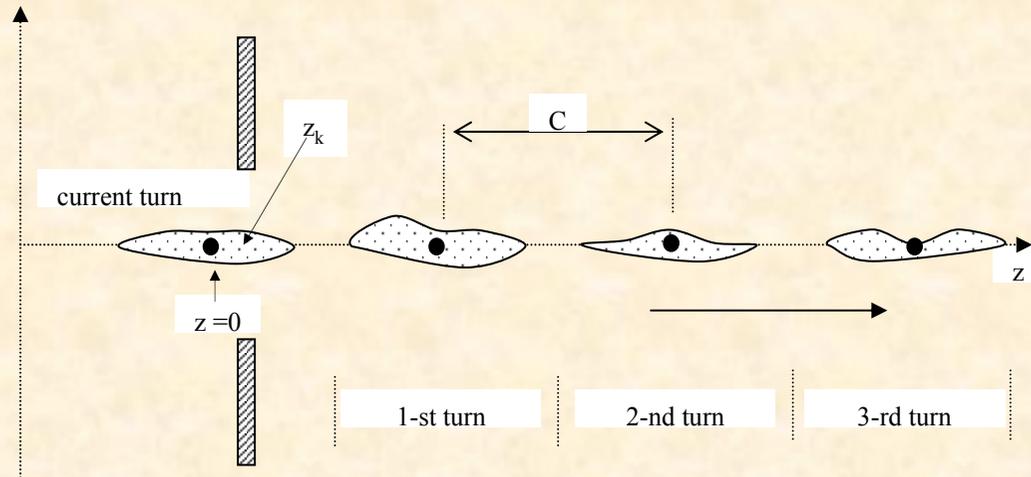
Numerical solution on the left shows a group of particles within a short slice.

The analytic solution (right) represents an infinitely thin slice and is therefore less fuzzy.

The stability threshold in intensity of the beam has been predicted within 5%.

V. Danilov, J. Galambos, J. Holmes,, "Transverse Impedance Implementation in ORBIT," PAC'01, Chicago, IL, June 2001, p. 1752

TI Time Domain Module Benchmark



Multiple passages of a bunched beam through a resonant structure.
C is the accelerator circumference

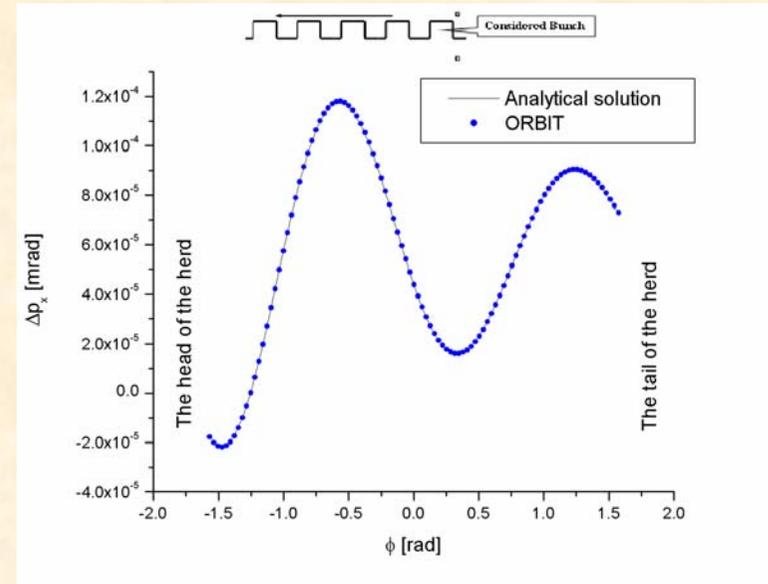
The transverse wake force F is experienced by a test charge e at the position z_k in the current bunch. J_1 is the longitudinal density of the dipole moment of the beam. W_1 is the wake function; it describes the shock response to a δ -function beam which carries the dipole moment.

$$\bar{F}(z_k) = -e \cdot \int_{z_k}^{\infty} j_1(z) \cdot W_1(t_k - t) dz$$

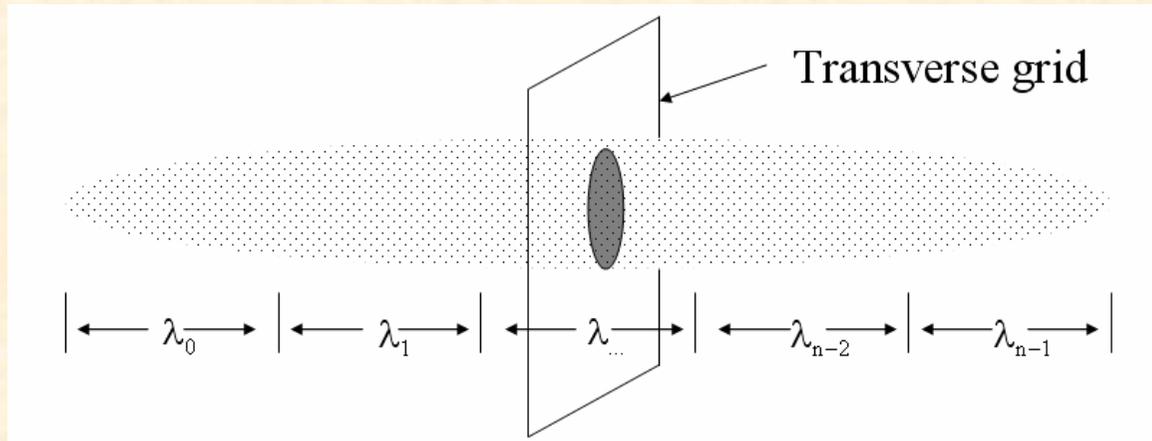
An infinite number of passages can be accounted in the case of a special wake function which satisfies the phasor condition.

$$W_1(z + D) = e^{\eta \cdot D} \cdot W_1(z)$$

The transverse momentum kick vs. particle position in the bunch after 4 previous passages through the TI lattice element.



2.5D Space Charge Module Algorithm



$$\vec{F}_{\perp}(\vec{r}_{\perp}) \propto \int \rho(\vec{r}'_{\perp}) \frac{\Delta \vec{r}_{\perp}}{\Delta r_{\perp}^2} d\vec{r}'_{\perp}$$

$$\vec{F}_{\perp,i} \propto \frac{\lambda_i}{\sum \lambda_j} \vec{F}_{\perp}$$

$$\Delta \vec{p}_{\perp} = \int_L \vec{F}_{\perp}(\vec{r}) dt \approx \langle \vec{F} \rangle \frac{L}{\beta \cdot c}$$

The 2.5D space charge model:

- It is implemented as a series of transverse momentum kicks between the lattice elements.
- Particles are binned in a 2D rectangular grid.
- The potential is solved using a fast FFT solver.
- The transverse momentum kicks are weighted by the local longitudinal density.
- Conducting wall (circular, elliptical, or rectangular beam pipe) boundary conditions can be used.
- There is also an alternative direct force solver without beam pipe.

We call this model 2.5D.

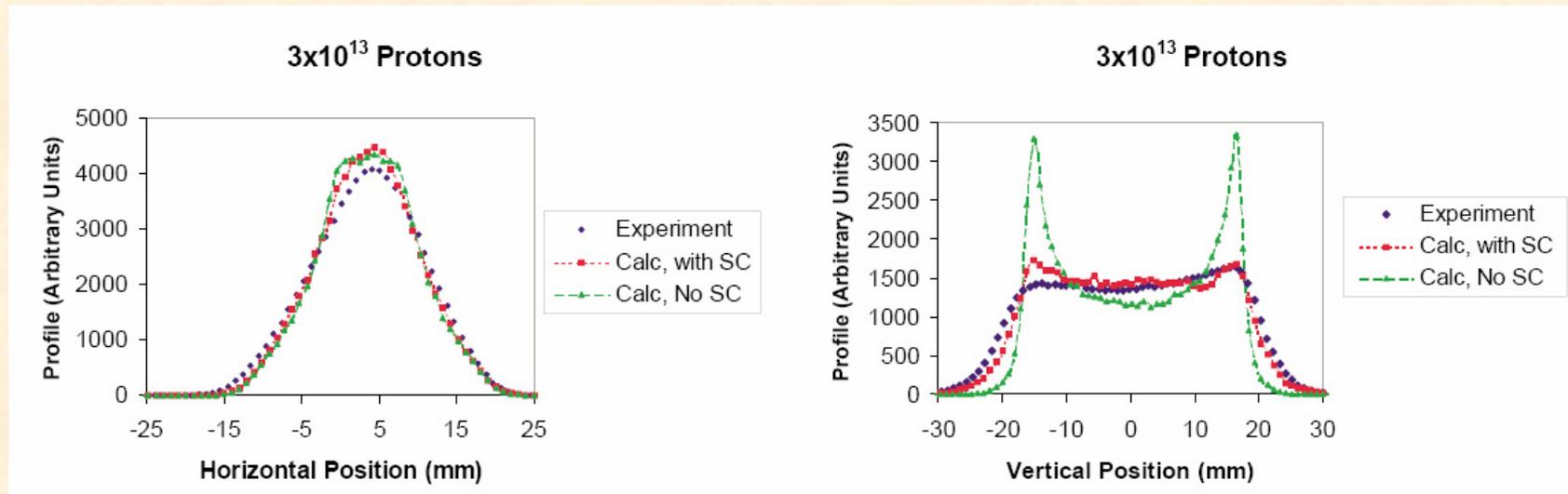
2.5D Space Charge Module Benchmark

This module has been successfully used to explain the beam transverse distribution in the PSR ring:

J. D. Galambos, S. Danilov, D. Jeon, J. A. Holmes, and D. K. Olsen,
Comparison of simulated and observed beam profile broadening in the Proton Storage Ring and the role of space charge. Phys. Rev. ST Accel. Beams 3, 034201 (2000)

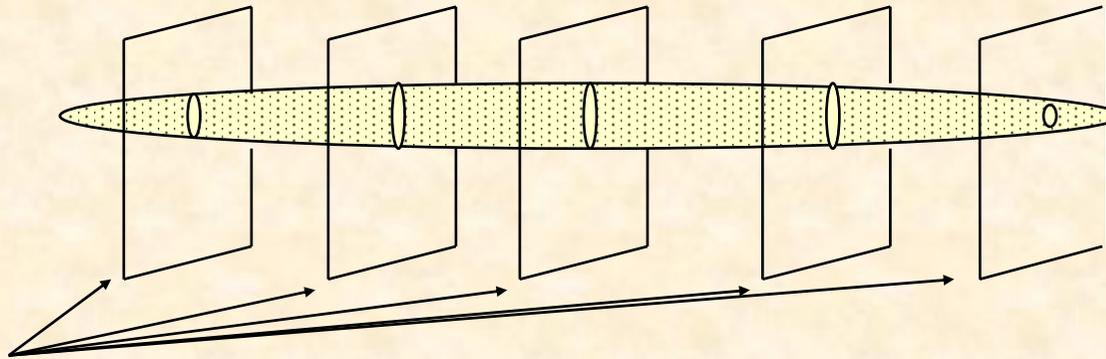
S. Cousineau, J. Holmes, J. Galambos, A. Fedotov, J. Wei, R. Macek
Resonant beam behavior studies in the Proton Storage Ring. Phys. Rev. ST Accel. Beams 6, 074202 (2003)

- Transverse beam profiles are observed to broaden with increasing intensity in the PSR.
- Inclusion of space charge effects improves the agreement between the experimentally observed profiles and the calculated profiles.
- The comparisons are made for a range of injected intensities.



The effect of the space charge on the calculated beam profiles, for the case with no closed orbit bumps during injection and at the highest intensity.

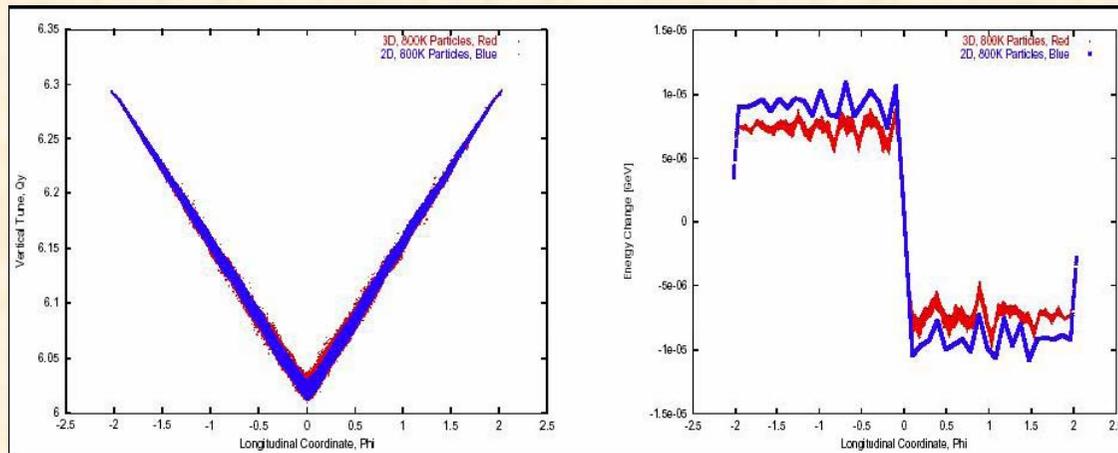
3D Space Charge Module Algorithm



2D SC problem with the boundary condition

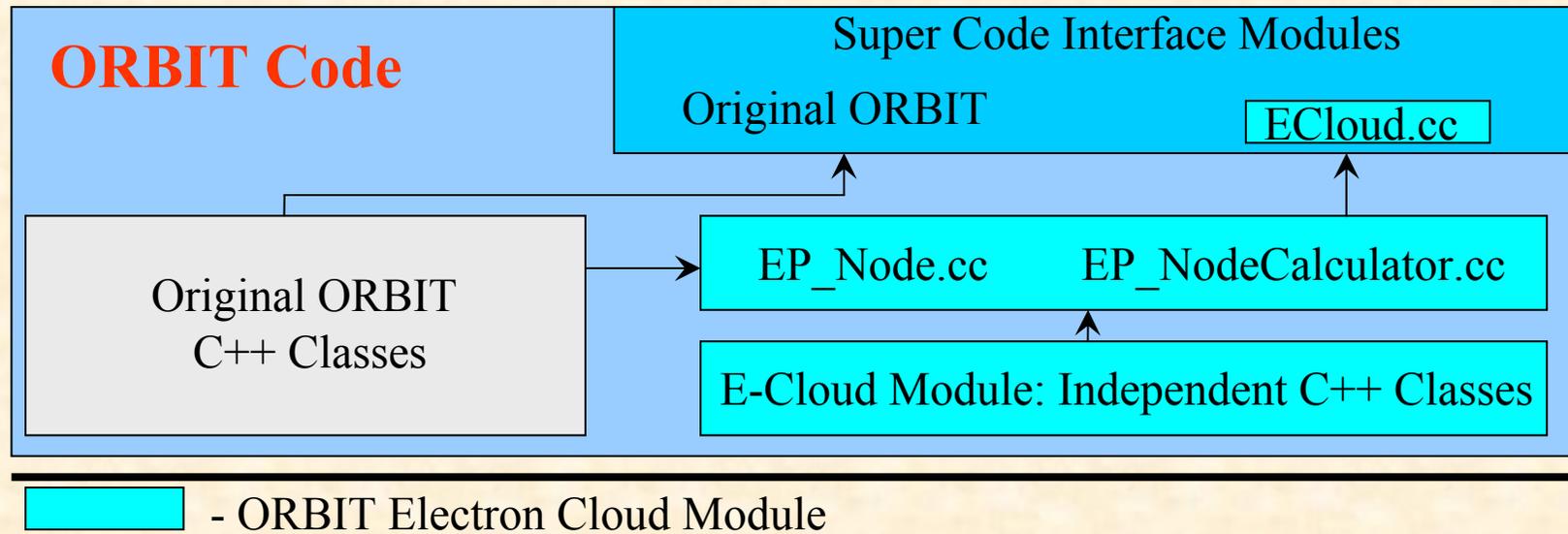
The boundary at the fixed potential

- The 3D space charge model is a simple generalization of the 2.5D routine. Particles are distributed to a 3D rectangular grid using a second order scheme.
- Simulations with this module require a multiple CPU computer or parallel cluster, because the numbers of particles and grid points are proportional to the number of transverse slices in the 3D grid.



3D space charge benchmark for triangular charge distribution: a) tune shifts vs. position, b) longitudinal force vs. position. 2.5D and 3D results agree with each other and with analytic calculations

ORBIT: Electron Cloud Module

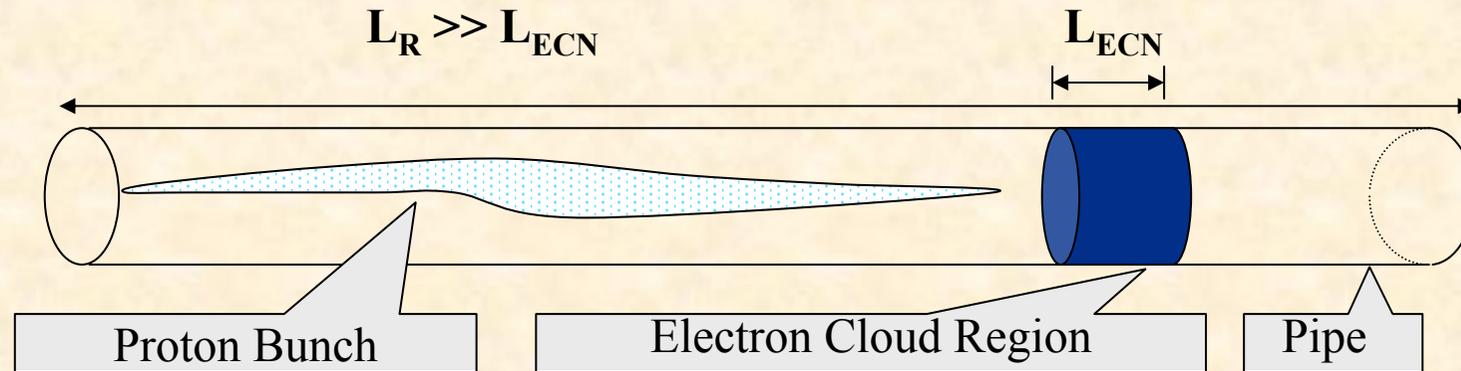


**Electron Cloud Module has a weak link to ORBIT.
It can be used outside ORBIT.**

Electron Cloud Module:

- **Electron cloud dynamics in electromagnetic fields**
- **Coupled dynamics of the electrons and protons**
- **Realistic surface model (M.T.F Pivi and M.A. Furman's model, PRST-AB 6 034201 (2003))**
- **Accelerator lattice can have arbitrary number of Electron Cloud Nodes**

Electron Cloud Node (ECN) Algorithm



The PIC method for electrons' and protons' electromagnetic fields

Protons' dynamics inside the bunch:
Each proton gets a momentum kick

$$\Delta \vec{p} = \frac{L_{eff}}{L_{ECN}} \cdot q \cdot \vec{E}_{cloud} \cdot \Delta t$$

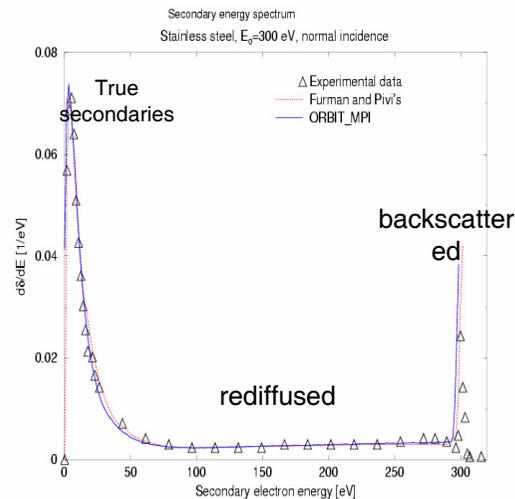
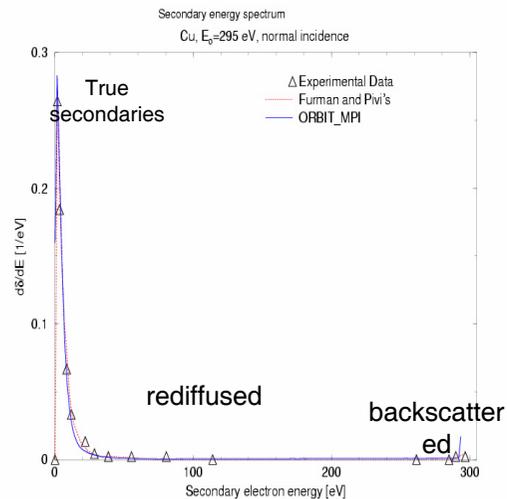
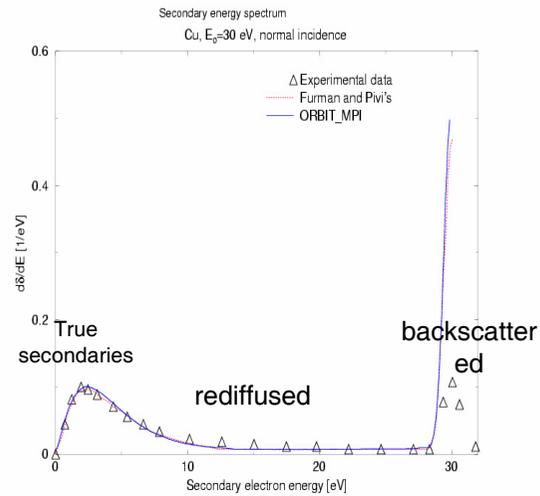
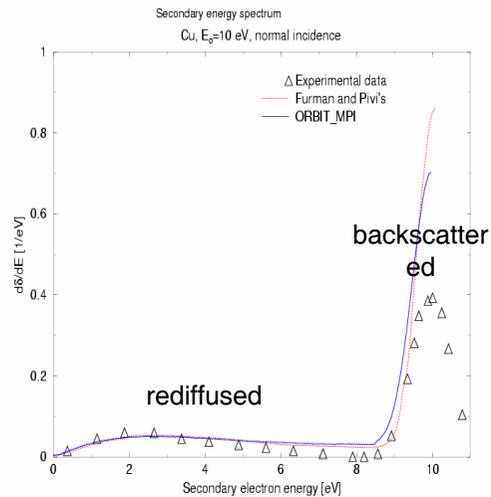
Electrons' dynamics inside ECN:

- time is a independent variable
- electromagnetic forces from:
 - proton bunch
 - electrons
 - conducting walls
 - external magnetic fields
- Furman-Pivi surface model

The effective length is our parameter.

Electrons' and protons' dynamics are tied together

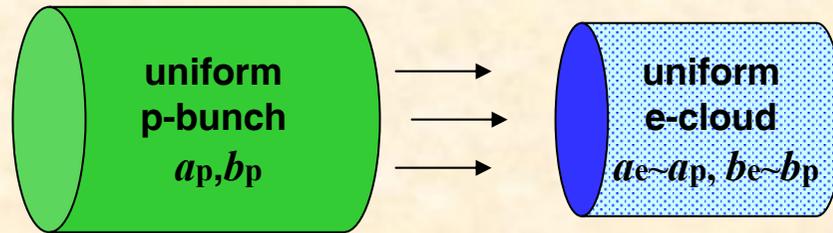
Surface Model Benchmark



The secondary electron energy spectra from normal incidental electrons on copper and stainless steel surfaces

The ORBIT spectra ($E_0=10, 30, 295$ eV for copper, 300 eV for stainless steel) match Furman and Pivi's simulation, PRST-AB 5 124404 (2002),

Two Stream Instability Analytically Solvable Model



Ref: D. Neuffer *et. al.* NIM A321 p1 (1992)

Centroid oscillation model of uniform line densities of proton and electron

$$y_{p,c} = A_p \text{Exp}[i(n\theta - \omega t)], \quad y_{e,c} = A_e \text{Exp}[i(n\theta - \omega t)]$$

The relation is valid under **linear force** inside the streams

Dispersion relation (no frequency spread)

$$(\omega_e^2 - \omega^2) \{ \omega_\beta^2 + \omega_p^2 - (n\omega_0 - \omega)^2 \} = \omega_e^2 \omega_p^2$$

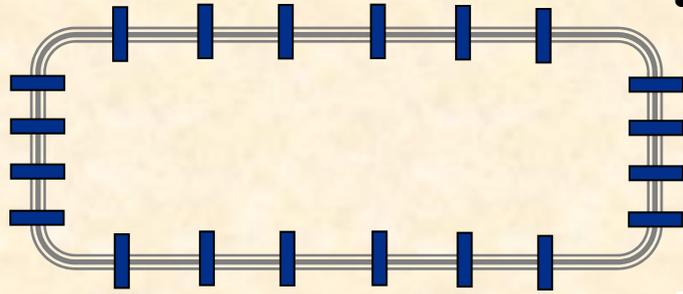
$$\omega_{p,V}^2 = \frac{4\lambda_e r_p c^2}{\gamma b_e (a_e + b_e)}, \quad \omega_{e,V}^2 = \frac{4\lambda_p r_e c^2}{b_p (a_p + b_p)}$$

The dispersion relation has complex solutions (instability) near the frequencies

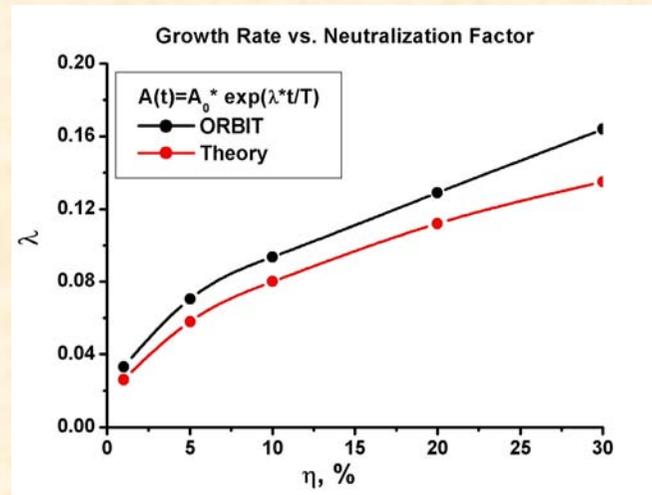
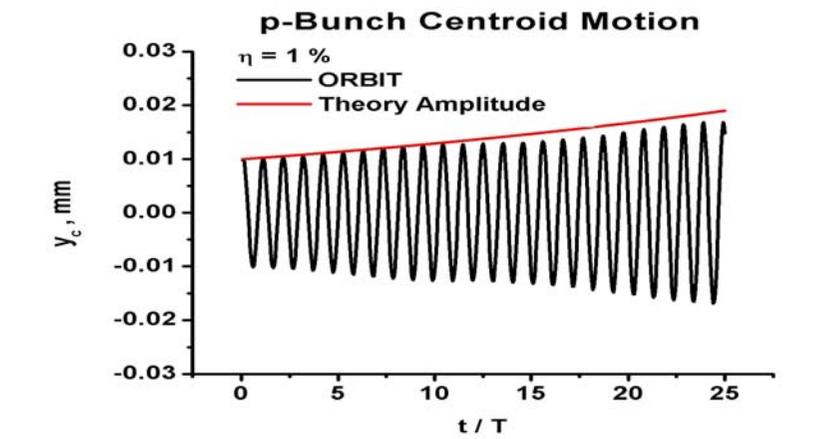
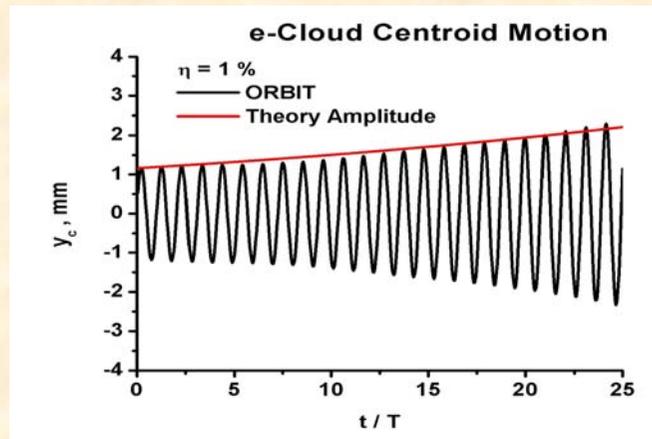
$$\omega \sim \omega_e \text{ and } \omega \sim (n\omega_0 - \omega_\beta)$$

This model has nothing to do with the surface model

Two Stream Instability Benchmark



- Uniform Focusing Lattice:**
- ❖ 20 Transport Map Nodes
 - ❖ 20 Electron Cloud Nodes (ECNs)
 - ❖ About one wavelength of EC instability

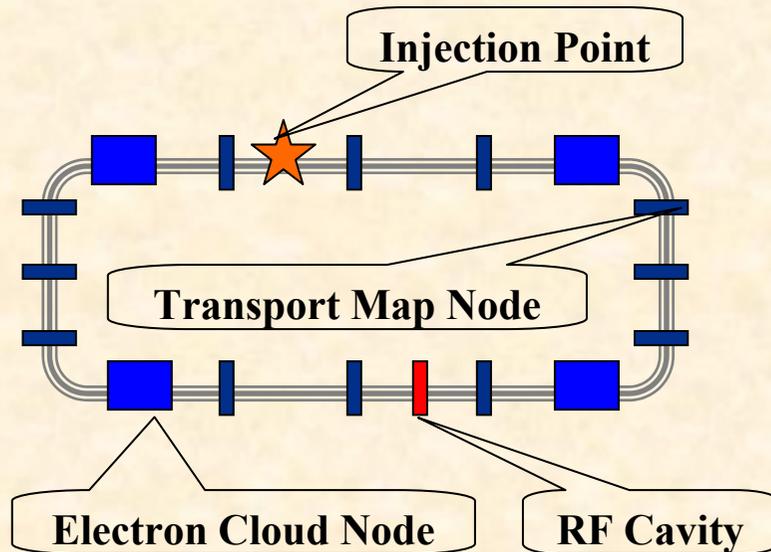


$$\eta = \rho_e / \rho_p$$

Neutralization factor is the ratio of electron cloud and proton bunch densities.

We can not expect exact agreement between results, because small oscillations of the protons are accompanied by significant electrons oscillations (~100 times), which destroy the basic assumptions of the model.

EC Module Benchmark against PSR Data. Model.

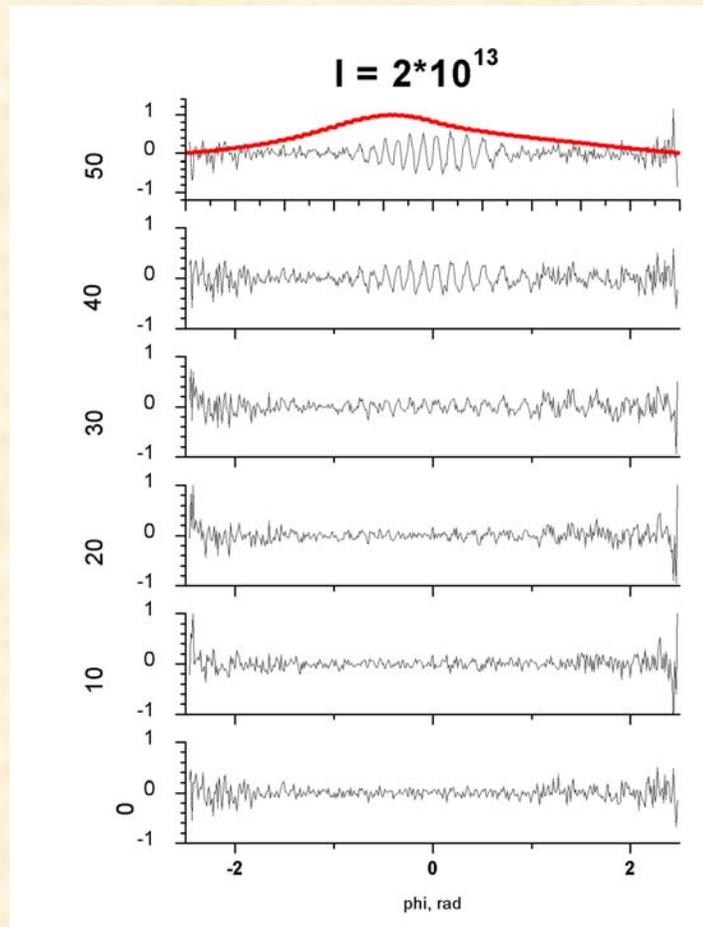


- Lattice of the model includes:
- drifts, dipoles, and quadrupoles
 - rf-buncher node
 - injection node
 - longitudinal space charge node
 - inductive inserts
 - one or few Electron Cloud Nodes (ECNs)

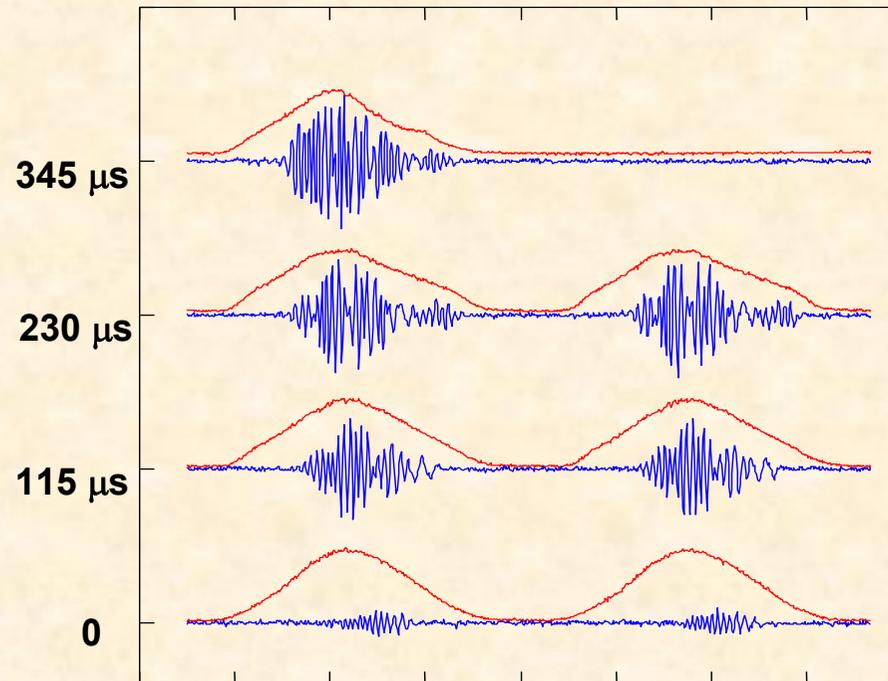
Stage 1 (preparation)	Stage 2 (main)
<p>3200 turns of injection</p> <p>All ECNs are switched off</p> <p>10,000,000 macro-protons at the end</p>	<p>No injection</p> <p>Several tens of turns</p> <p>ECNs are switched on</p>

Benchmark with PSR: Instability Exists

Simulations



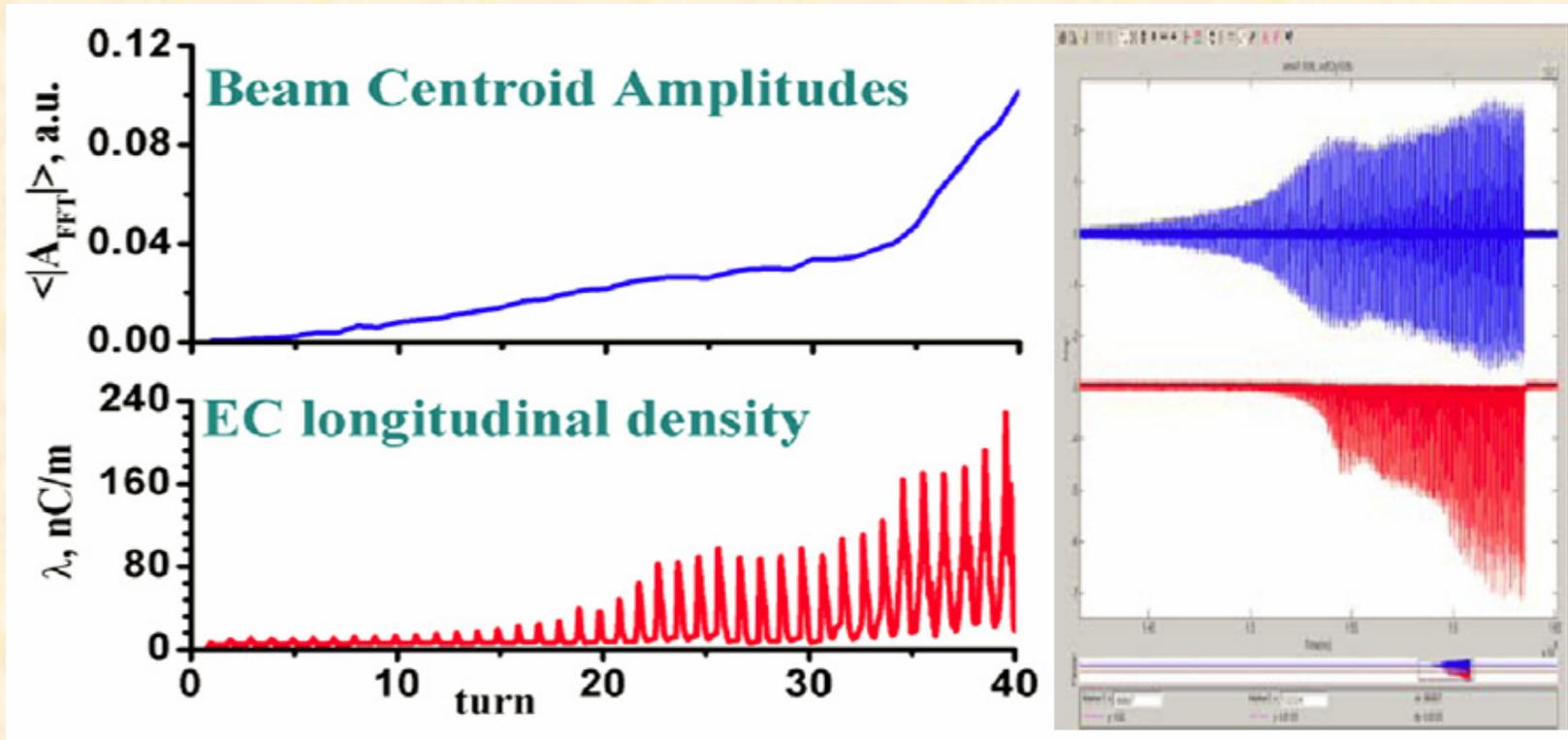
PSR Data



Robert Macek Talk, LANL, 3/15-18/04
Vertical difference signals (**blue**) from a
short stripline BPM and beam pulses
from a wall current monitor (**red**).

Data taken Apr. 14, 1997

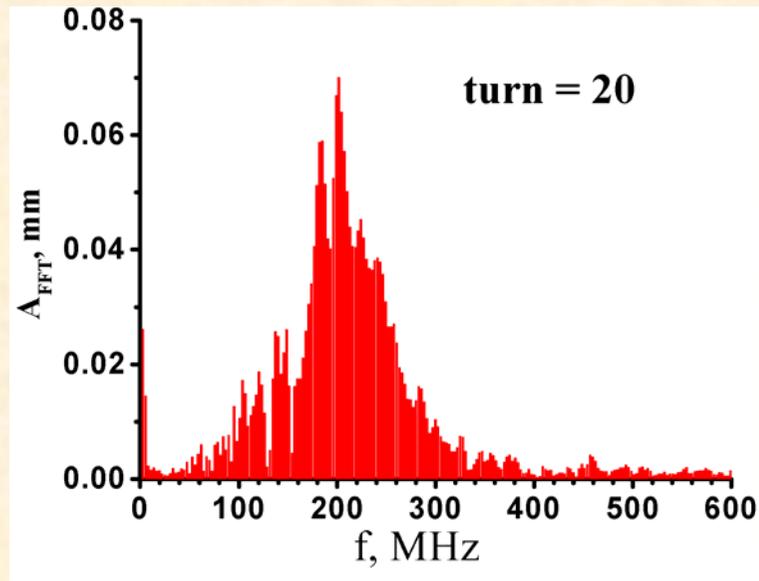
Benchmark with PSR: EC-Protons Coupling



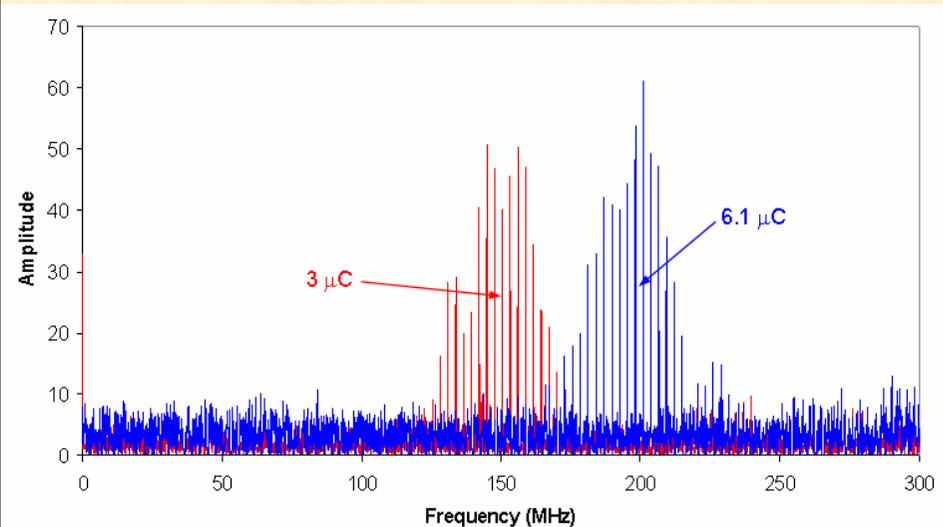
Instability development for one ECN in the PSR lattice. The left half is the simulation results, and the right half is the real PSR data.

The coupling between proton instabilities and electron production. An intense electron flux coincides with high amplitude coherent proton bunch oscillations at the onset of substantial beam losses.

Benchmark with PSR: Frequency Spectrum – One ECN



Simulations



Robert Macek Talk, LANL, 3/15-18/04

PSR Data

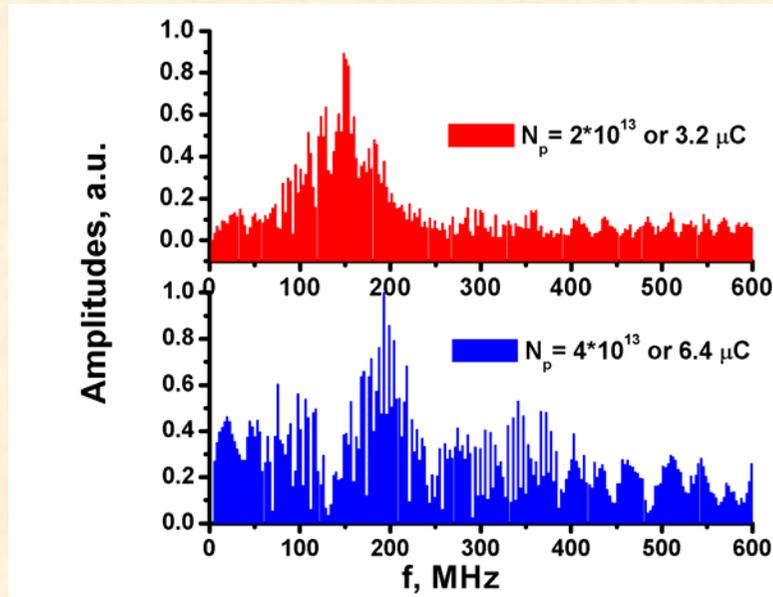
Discrepancies:

- ❑ Peak frequency too high (about 200 MHz instead of 150 MHz)
- ❑ Instabilities starts near the center of the bunch (should be tail)
- ❑ Growth rate is too high

It was only one ECN in the lattice. Let us use more.

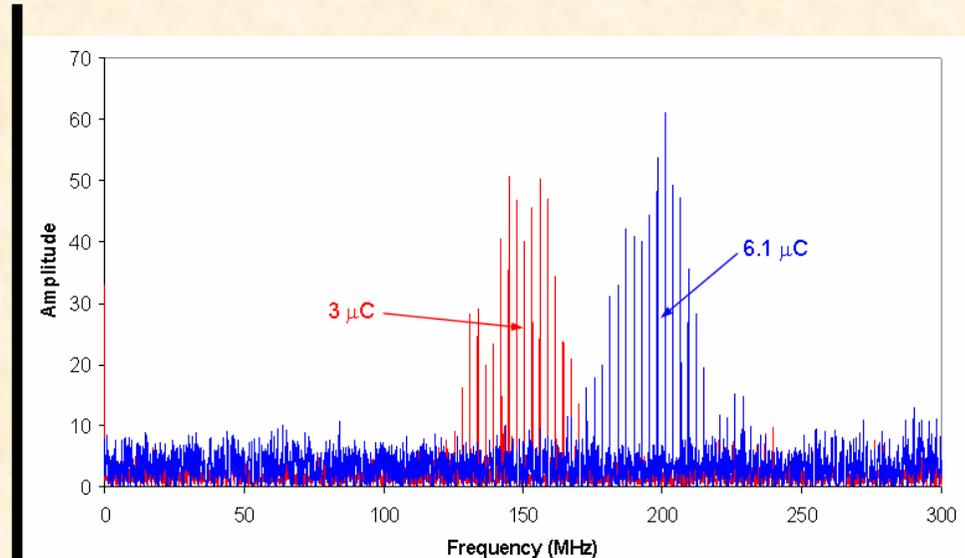
Benchmark with PSR: Frequency Spectrum – 5 ECNs

5 ECNs were distributed along the lattice



turn = 20

Simulations



Robert Macek Talk, LANL, 3/15-18/04

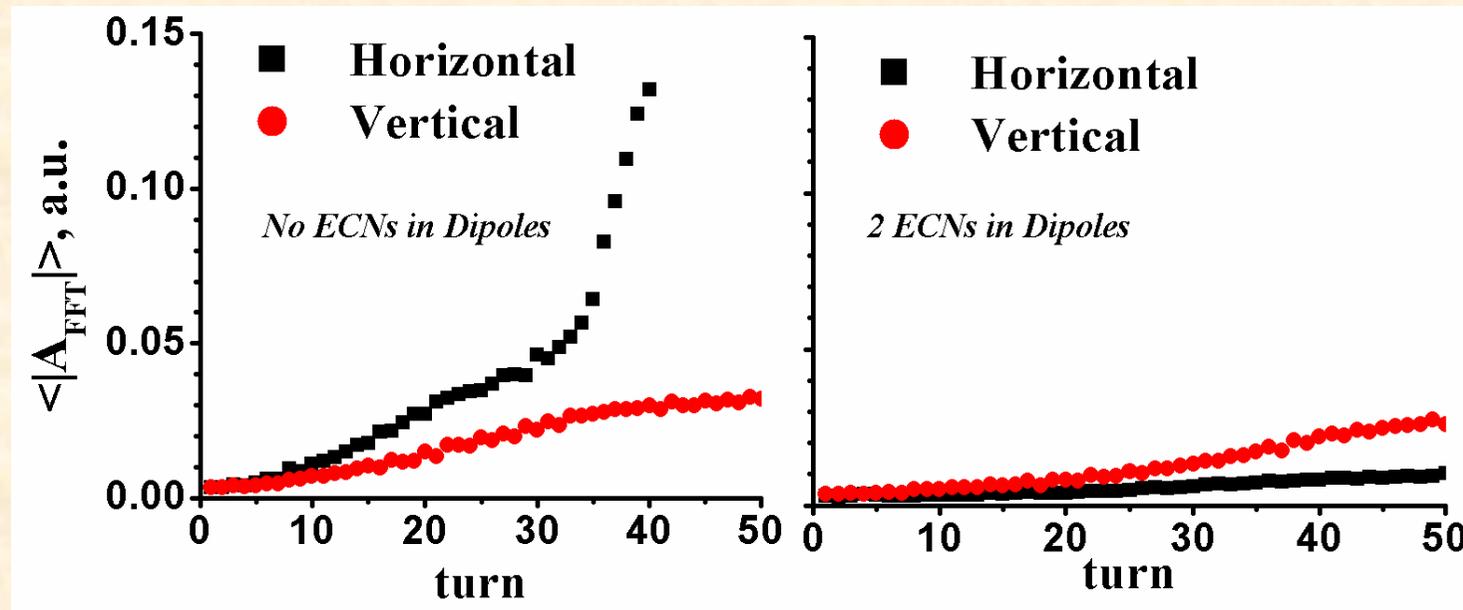
PSR Data

Frequency spectra have been fixed

$$f_{peak} \approx \sqrt{N_p}$$

Benchmark with PSR: Asymmetry in Directions

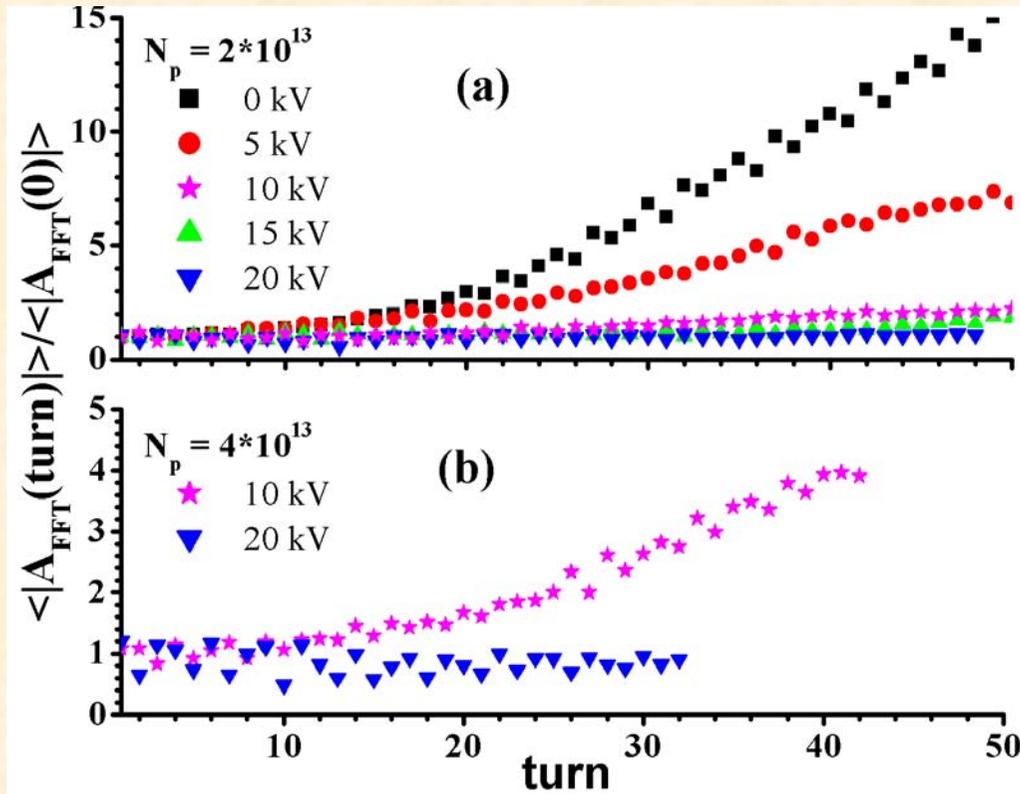
An asymmetry in directions where instabilities occur. The instabilities have been seen mostly in the vertical direction.



Total number of ECNs is 7 (5+2):

- The vertical instability is dominant (electrons moving vertically in dipoles)
- The growth rate becomes more realistic

Benchmark with PSR: Instability Suppression



The time evolution of average amplitudes of the vertical proton beam oscillations. (a) 3.2 μC and (b) 6.4 μC cases.

The EC--related instabilities in PSR are controlled by the voltage to the rf cavities. Higher voltage leads to a larger energy spread in the bunch.

The experimental data show that the maximum stable charge of the bunch scales linearly with the rf voltage.

A set of simulations was carried out in an attempt to reproduce this dependence. We ran simulations for 3.2 and for 6.4 μC bunches at several values of the voltage. For all runs, a lattice with 7 distributed ECNs was used.

Benchmark with PSR: Conclusions

ORBIT EC Model demonstrated:

- **Existence of the instability.**
- **The coupling between proton instabilities and electron production. An intense electron flux coincides with high amplitude coherent proton bunch oscillations at the onset of substantial beam losses.**
- **Agreement with the observed frequency spectrum of the proton bunch oscillation.**
- **An asymmetry in directions where instabilities occur. The instabilities have been seen mostly in the vertical direction.**
- **The relationship between the maximum number of protons in the bunch and the threshold rf voltage.**

Conclusions

The ORBIT code can be successfully used for the realistic simulation of collective effects in accumulator rings.

These effects include:

- impedances**
- space charge**
- electron clouds**

The flexible structure of the code

- allows combining these effects in user defined configurations**
- presents the possibility of further development of ORBIT**