# Collective Effects and Instabilities in Space Charge Dominated Beams

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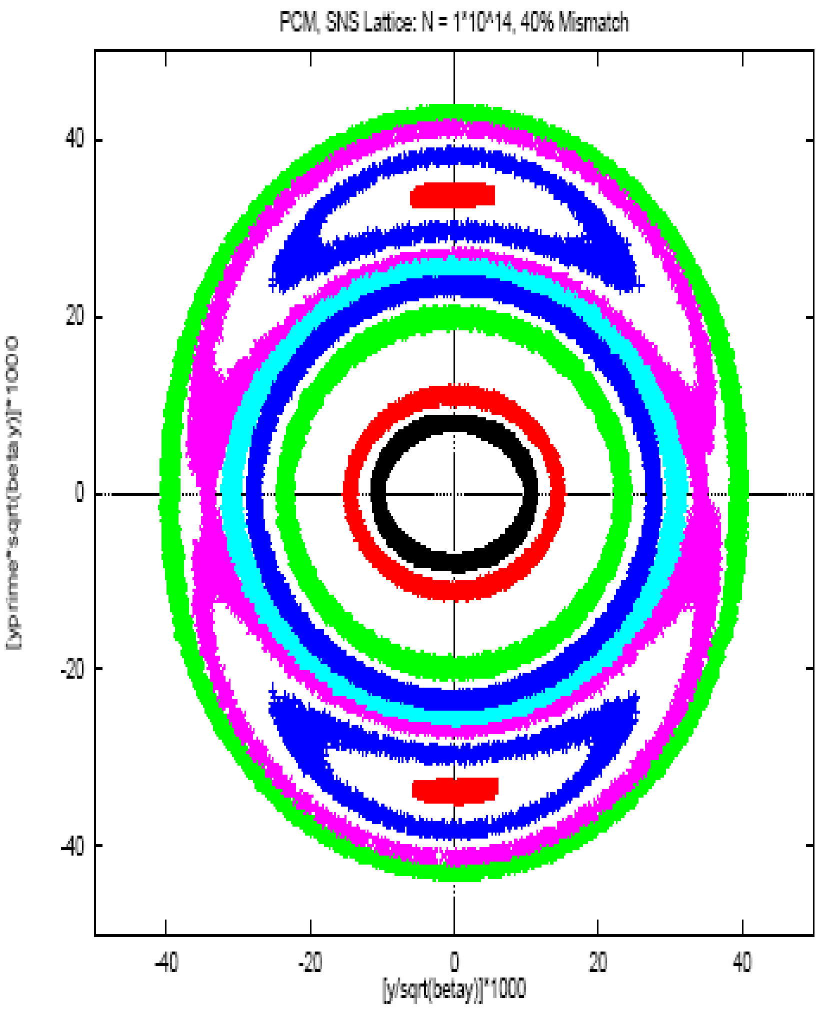
# Scope and Outline

- **This presentation will illustrate the use of computer simulations to study collective beam dynamics in high intensity proton rings.**
- **More and more, computer codes are used to perform desktop experiments that provide**
  - **thorough control**
  - **analysis and visualization**
- **Simulations**
  - **confirm and demonstrate the limits of theory**
  - **aid in the understanding of experimental results**
  - **provide guidance on design and operational issues**
- **We will consider:**
  - **Space Charge Resonances**
    - **Parametric Resonance in Mismatched Beams**
    - **Intrinsic Resonances of Anisotropic Beams**
    - **Half Integer (Envelope Integer) Resonance Crossing**
    - **Space Charge and Higher Order Lattice Resonances**
  - **Longitudinal Impedance Effects**
  - **Transverse Impedance Effects**
  - **Electron Cloud Studies**
  - **Self-Sustaining Bunched Space Charge Distribution**

# Parametric Resonance for Mismatched Beam

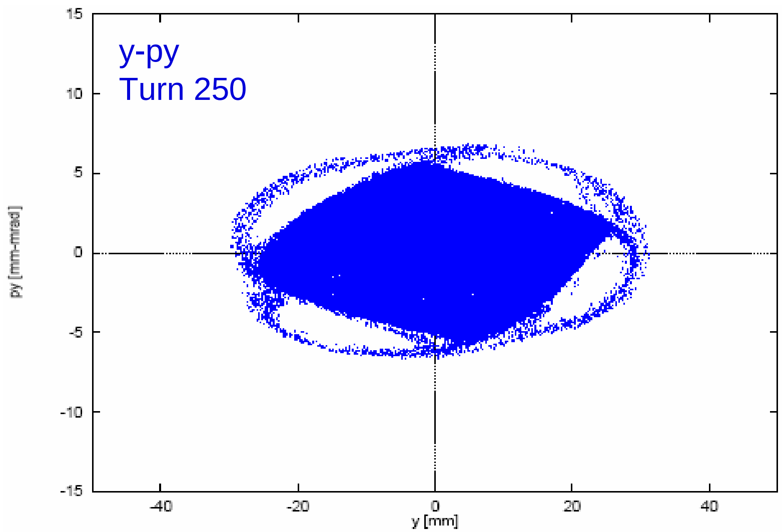
- For mismatched beams:
  - The envelope oscillates ~ twice the betatron frequency.
  - The relationship of the space charge depressed single particle tunes to the coherent envelope oscillation frequency leads to an m=2 resonance in the beam periphery.
  - Driven by the envelope oscillations, islands form about this resonance in the Hamiltonian topology of the single particles in the space charge potential.
  - Particles in the beam periphery can traverse the separatrix at the X-points, and thus become beam halo.
- Important in linacs, and maybe less important for rings.
- Studied analytically using envelope equations and computationally using particle core models and PIC codes.
- Investigated by many researchers: Gluckstern, Lagniel, Wangler, SY Lee, Ryne, Struckmeier, Reiser, Chen, Davidson, and their coworkers.

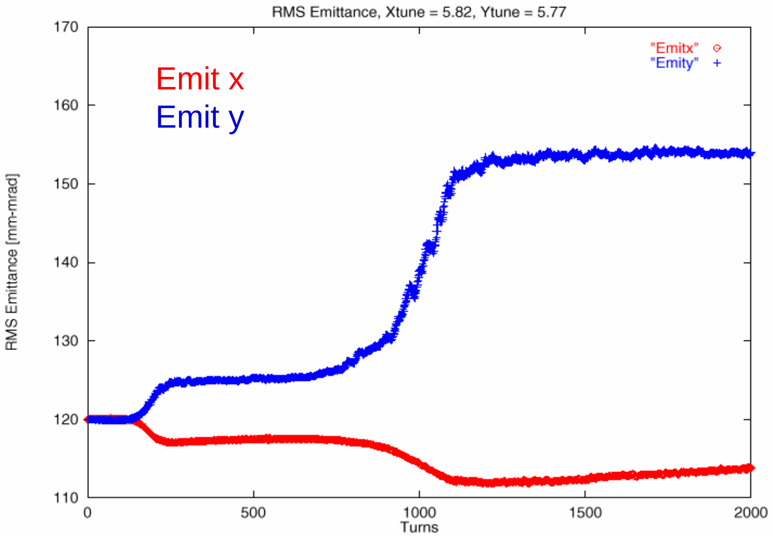


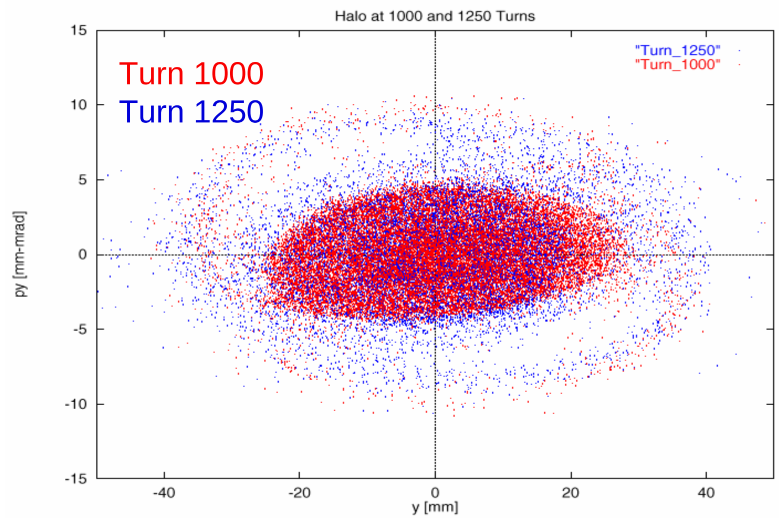
# Intrinsic Resonances of Anisotropic Beams

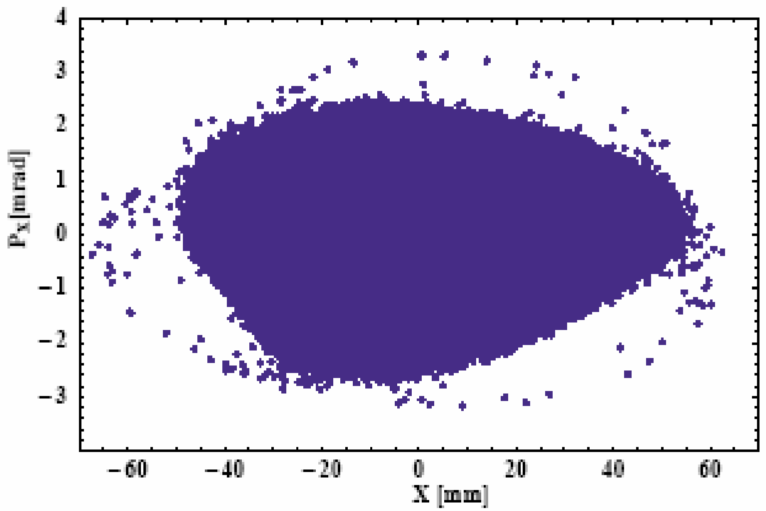
- Anisotropic beams having unequal energies in different directions can exchange energy between these different directions through coupling resonances driven by the beam space charge fields.
- They are independent of the details of the lattice structure, depending only on the relative emittances, average focusing strengths, and beam intensity.
- These resonances are accompanied by emittance exchange between directions and by halo formation in the direction receiving energy.
- Intrinsic coupling resonances are an important consideration in linacs and may also be of interest in rings when the tune separation is small.
- The theory of space charge coupling resonances has been studied most thoroughly by Hofmann using Vlasov equation analysis to determine detailed stability diagrams that demonstrate regions of stability and instability for anisotropic beams.
- Computational studies have been performed by Qiang and Ryne for linacs, and by Jeon, Fedotov, and Holmes for rings.
- An example taken from the CERN PS ring is presented in Poster WEPLT168 by Cousineau, Metral, and Holmes this afternoon.

# Two Examples of Intrinsic Coupling Resonances



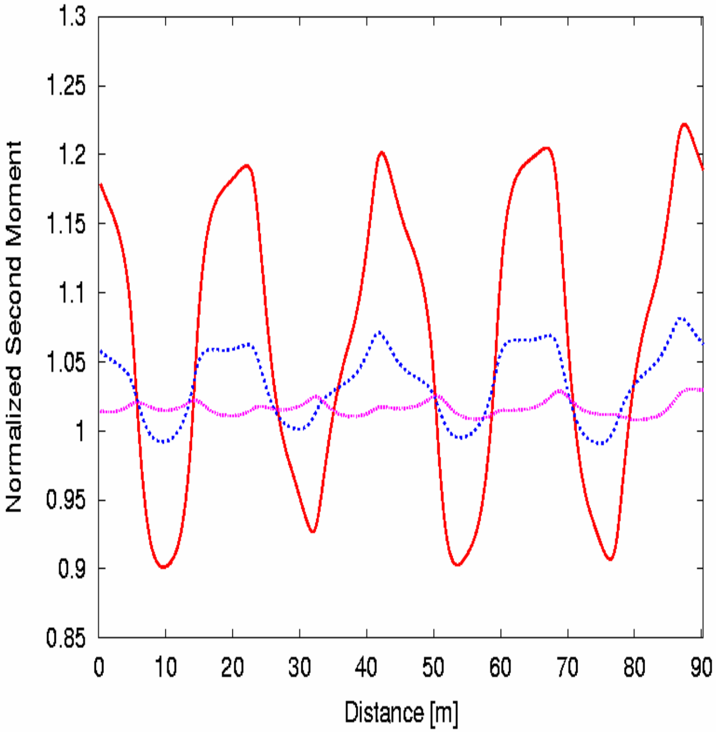



# Half Integer Resonance Crossing: Beam Integer Envelope Resonance in Rings

- This coherent effect involves an integer resonance of the beam envelope with a lattice perturbation. As a tune is brought near a half integer value from above, the coherent oscillation frequency of the beam envelope approaches the integer that is double that value. If the lattice contains perturbations at this integer value, a standing envelope modulation develops at that periodicity. This modulation can be thought of as a space charge induced adjustment of the lattice functions.

- This phenomena was studied in detail using envelope equations by Sacherer in his PhD thesis, and elaborated further by Hofmann, Struckmeier, Reiser, Gluckstern, Baartman, Machida, Fedotov, SY Lee, and others.

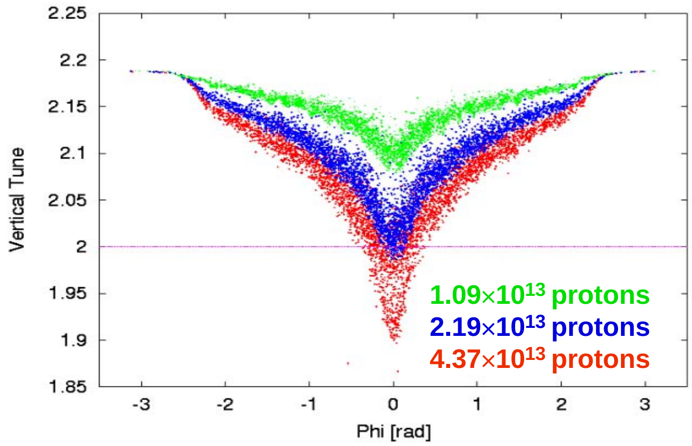
PSR: Bare tune Qy = 2.19. The envelope is modulated with 4 periods around the ring. $4.37 \times 10^{13}$ protons.

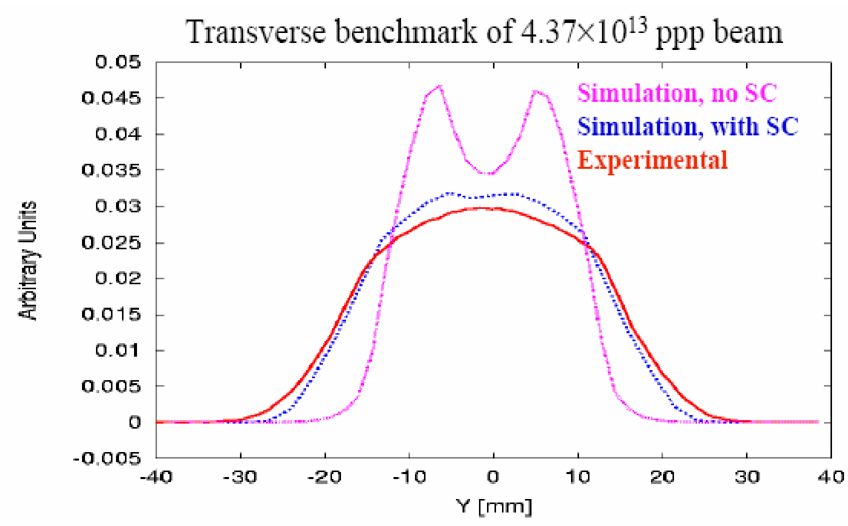


# Incoherent Tune Depression and Emittance Growth

- One of the interesting features of the half integer resonance comes from the relationship between the incoherent particle tunes and the envelope coherent frequency: incoherent tunes can cross the half integer resonance, in apparent violation of the single particle resonance condition, before the collective mode significantly affects the beam.

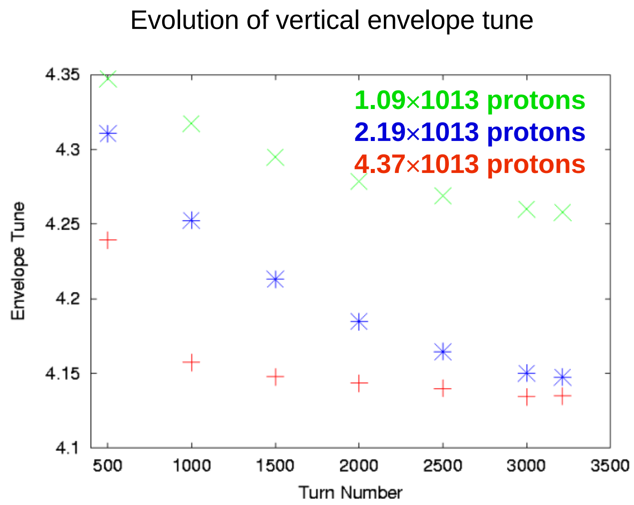
- One of the limitations of an envelope equation analysis is the inability to explain the emittance growth observed in association with the half integer resonance. The observed beam broadening is accompanied by emittance growth.

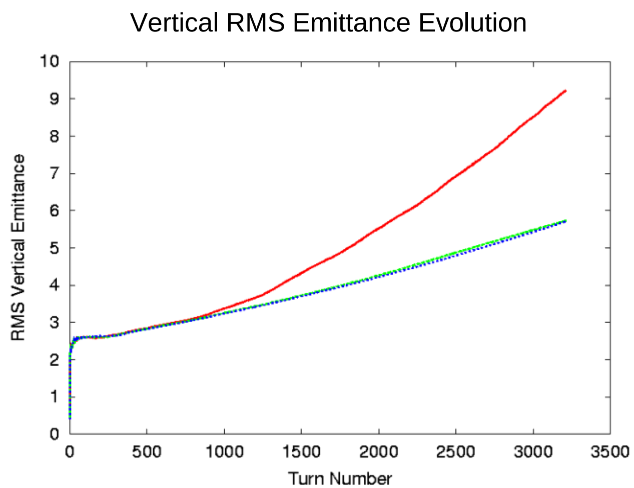


# Stopband and Emittance Growth in Integer Envelope Resonance

- The behavior of the emittance growth associated with the integer envelope resonance has been studied by Cousineau and coworkers, who determined the following:
  - As intensity increases, coherent envelope oscillation frequencies decrease until the collective envelope motion encounters an integer stopband.
- The response of the beam to this stopband is to increase its emittance (broaden) to weaken space charge forces just enough to maintain the position at the edge of the stopband. This broadening involves the whole bulk of the beam, it is not a halo forming process.
- The stopband is driven by lattice harmonics and can be corrected by removing those harmonics.

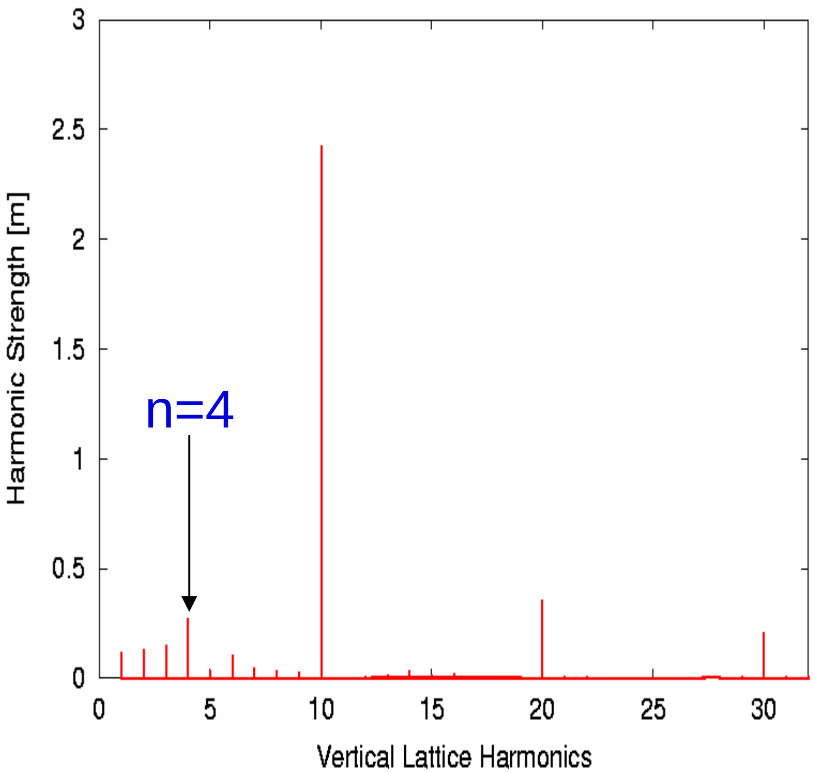


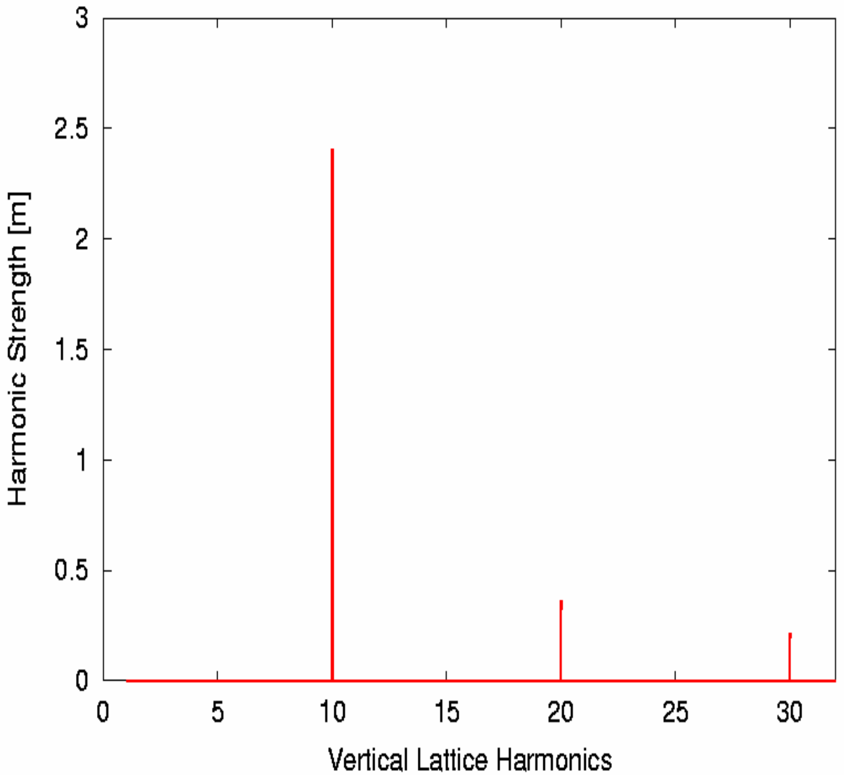
# Driving Term and Stopband Correction: A Symmetric Lattice Example

- The coherent resonance ($\nu_e \approx 4.0$) is driven by an n=4 lattice harmonic.
- Besides the structure harmonics (10, 20, 30...), n=4 is the strongest harmonic in the ring!
- Artificially remove n=4 driving term by creating perfectly symmetric PSR-like lattice.

Harmonic content of real PSR lattice

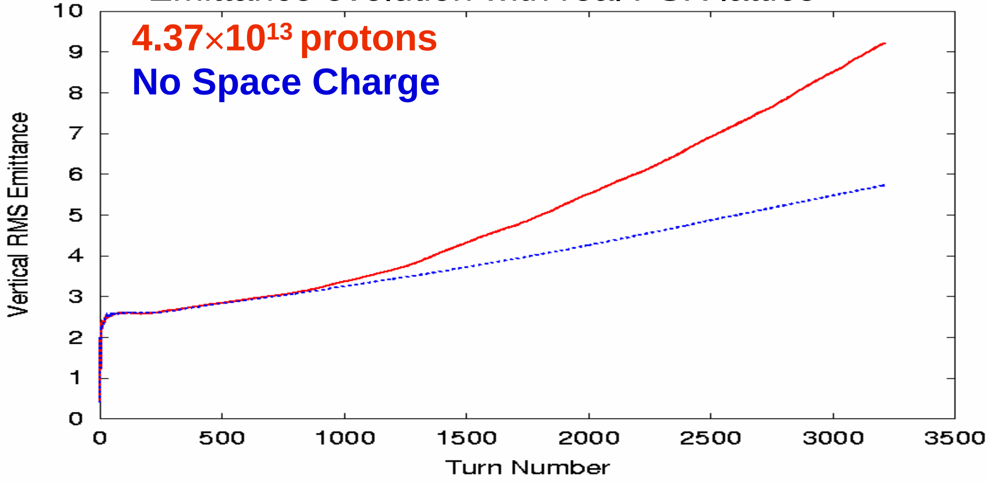



Harmonic content of symmetric PSR lattice

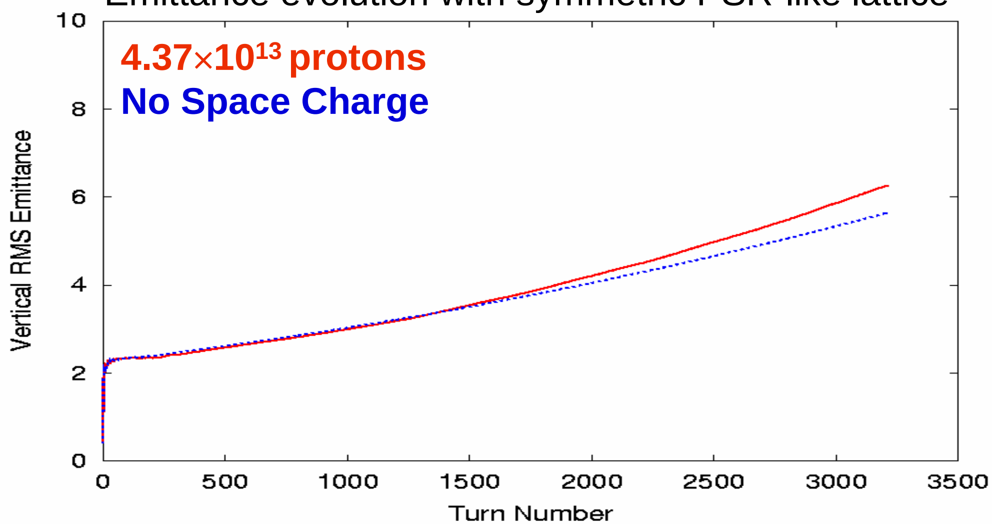


# Results of Symmetric Lattice Simulations

Emittance evolution with real PSR lattice




Emittance evolution with symmetric PSR-like lattice




- Symmetric lattice reduces space charge induced emittance growth.
- Some emittance growth can be caused by structure harmonics combining at higher order.
- In a uniform (average) lattice approximation, there are no harmonics, no emittance growth (not shown here)

# Higher Order Lattice Resonances with Space Charge and Their Correction

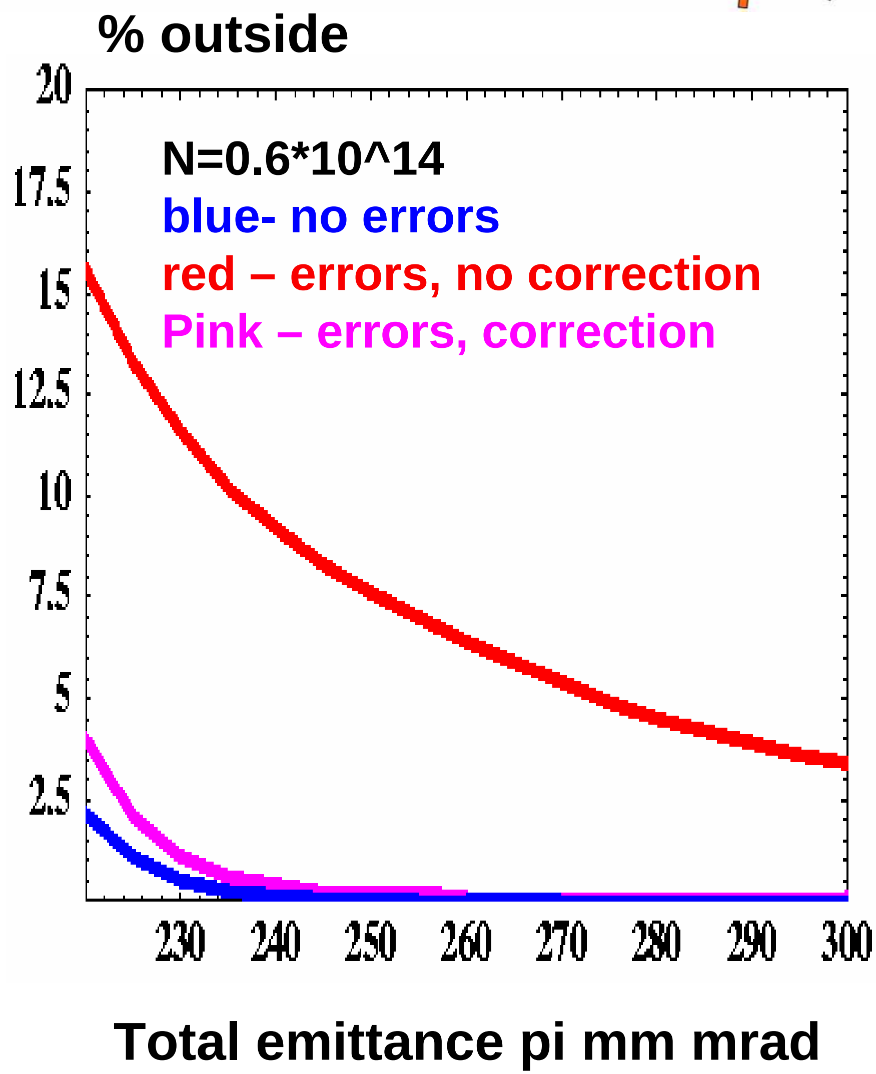
- Fedotov, Parzen, and coworkers have studied numerically the effect of higher (sextupole and octupole) order lattice imperfections and their correction for high intensity beams in the presence of space charge. They find that:
  - The resonances occur when collective, not individual particle, modes of oscillation are excited by lattice imperfections.
  - The resonances lead to a significant enhancement of the beam tail.
  - Magnetic correction of the driving terms ignoring space charge is sufficient to correct the resonances with space charge present.

# w.p. (6.4,6.3) - Correction of sum coupling resonance Qx+2Qy=19 and 3Qx=19 resonance (Fedotov, G. Parzen et al.)

- Experimentally, one can directly measure width of nonlinear islands by measuring tune vs amplitude, or by measuring portion of the beam locked into a resonance with good accuracy.

- We correct the islands – the best we can do in practice, and then study resonance crossing with the space charge, although correction via stopband was done also and was compared to the correction scheme via islands.

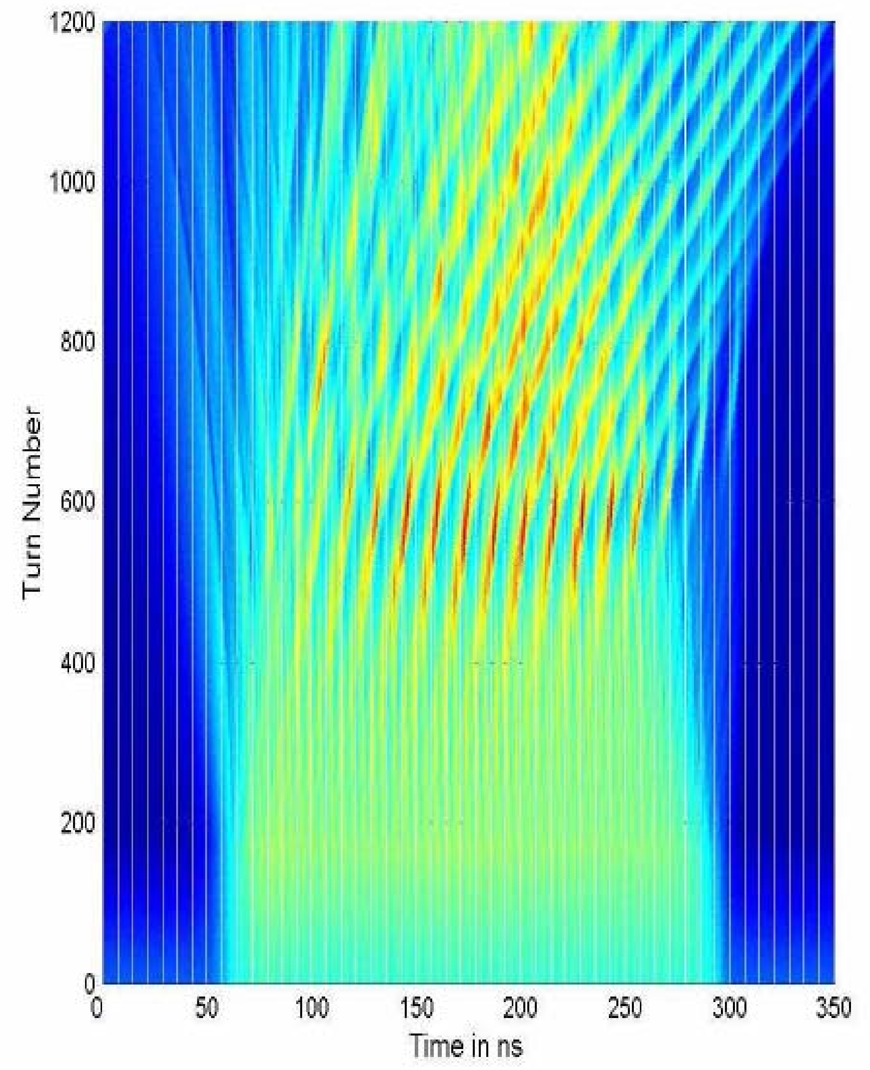
- Studies were done using DYNA and UAL codes.



# Longitudinal Instability with Space Charge: An Example from PSR (see Cousineau, Poster WEPLT169)

- Longitudinal beam dynamics in high intensity rings has been addressed computationally by a number of researchers including Prior, Koscielniak, and MacLachlan. Although the physics model for tracking in longitudinal codes is a simple 2D phase space, these codes contain many sophisticated features for acceleration, transition crossing, and beam manipulation, as well as models for wakefields and space charge.

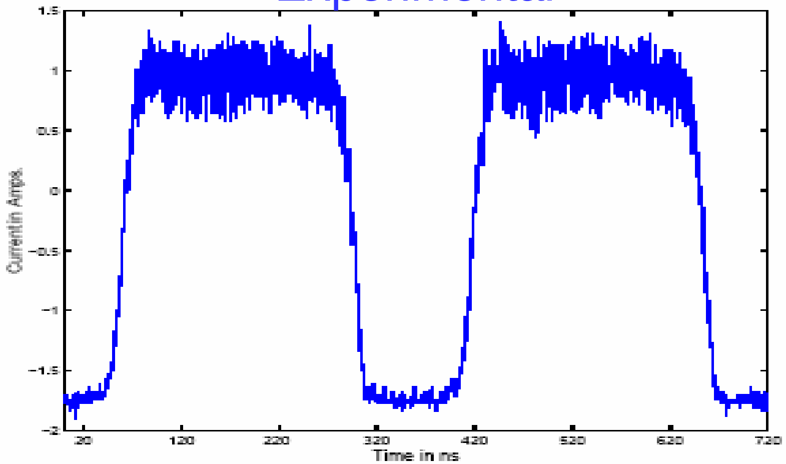
- The following calculations illustrate the simulation of a longitudinal instability in PSR at 72 MHz, which corresponds to a ring harmonic number of n=26. The instability is caused by the impedance of an inductive insert, when the insert is not heated. The calculations shown here were performed by S. Cousineau using the ORBIT Code with impedance taken from the Indiana University PhD thesis of C. Beltran and experimental data from R. Macek and Beltran.



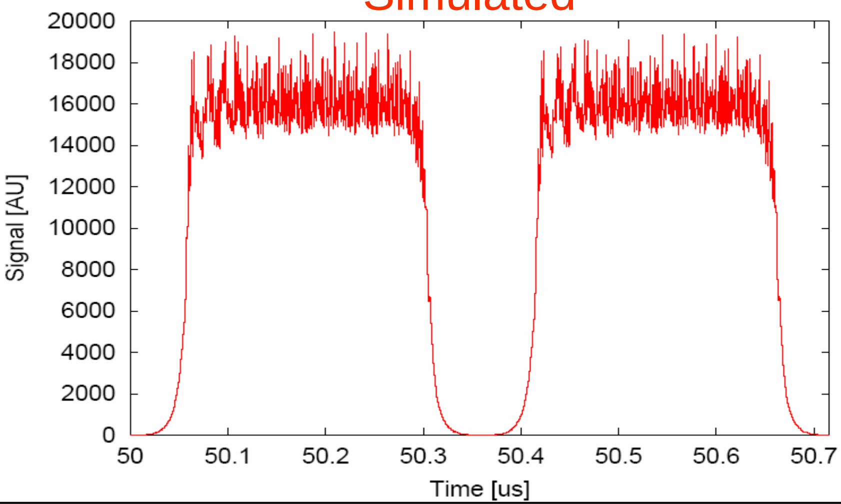
# Simulation Results – Profile Signature

## Signal @ end of injection

Experimental

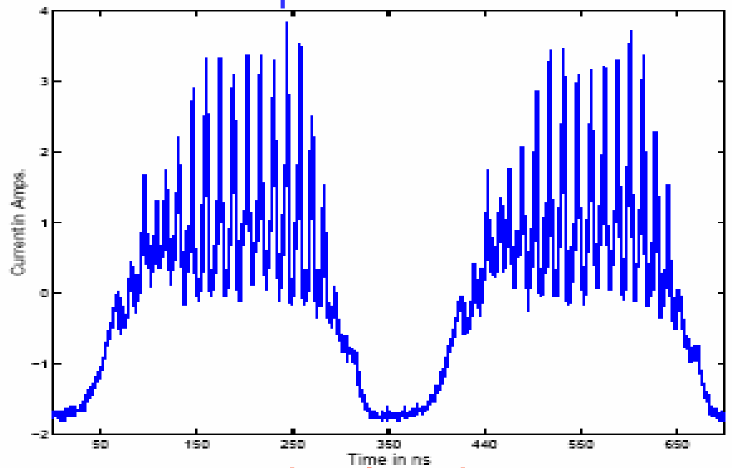



Simulated

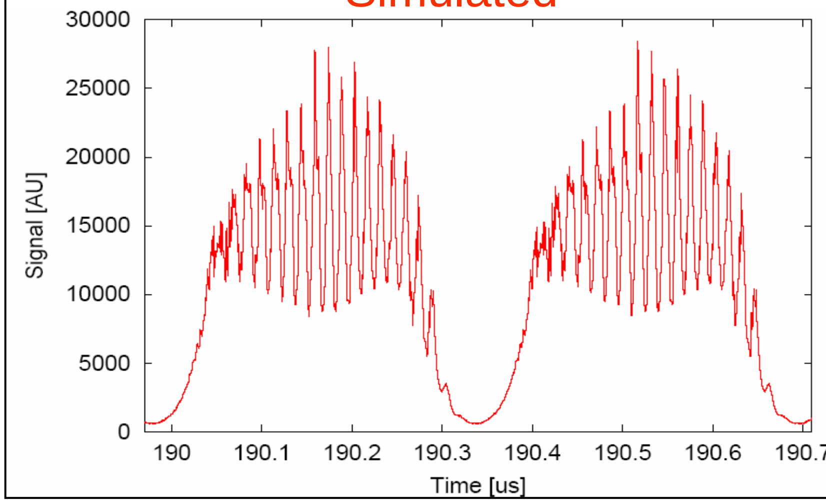



## Signal @ peak of instability

Experimental

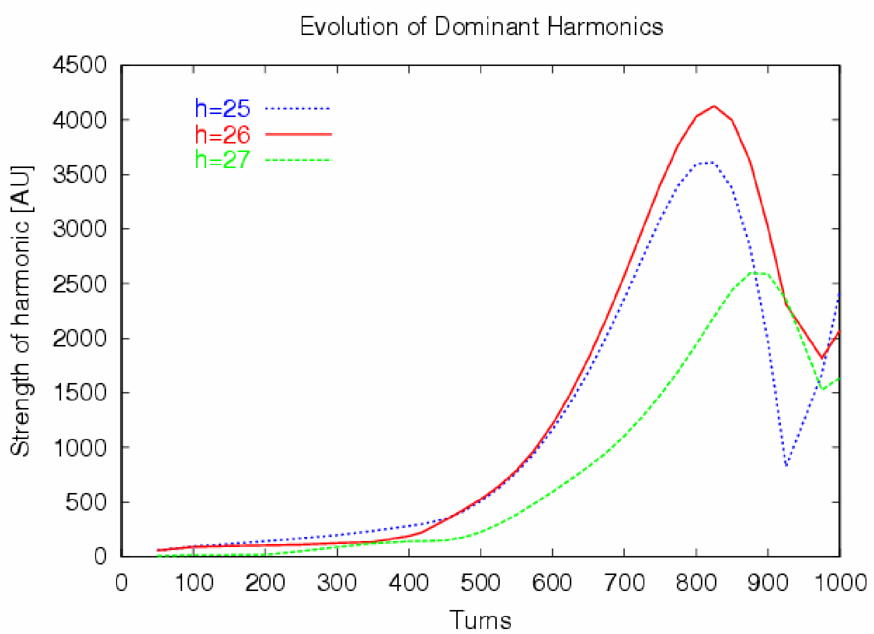


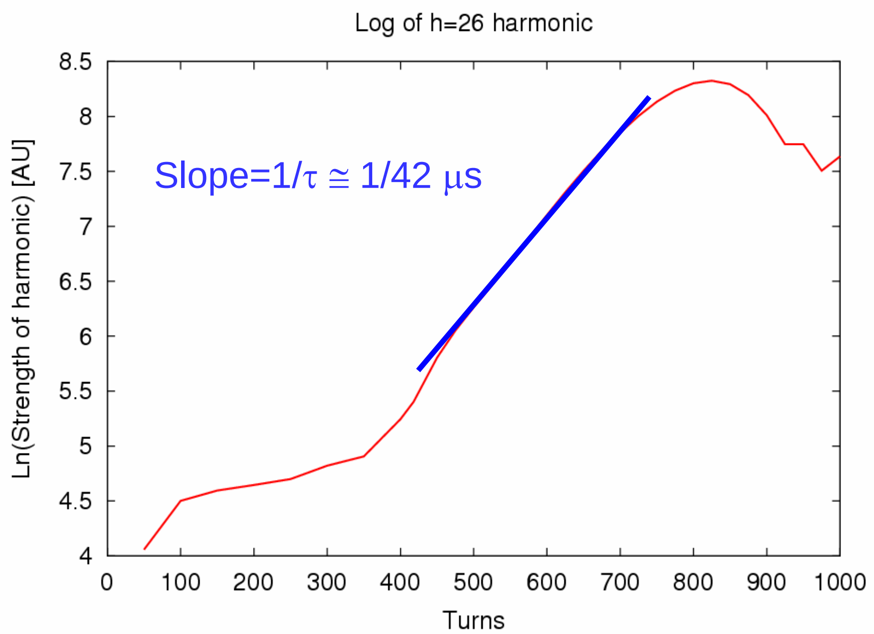

Simulated



# Simulation Results – Growth Rate and Threshold

- Exponential growth of harmonics observed.
- Dominant harmonic is n=26, same as experiment.
- Growth time of instability, $\tau \cong 42\ \mu s$; Experiment result is $\tau \cong 33\ \mu s$



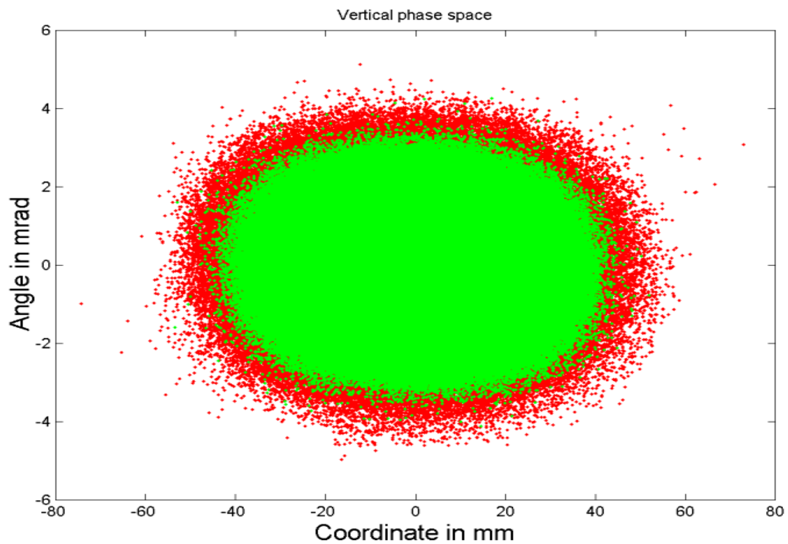



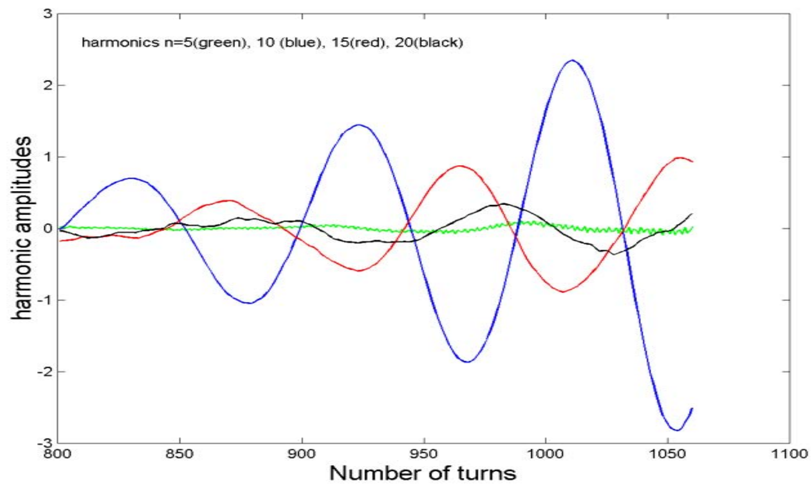

- Data set taken in 2002 to understand threshold; 2 inductors at room temp.
- Define threshold by beam intensity at which relevant harmonics rise coherently above noise level.
- Experimental threshold=80 nC; Simulated threshold=60-70 nC.

# Transverse Stability with Wake Fields and Space Charge

- The analytic theory of transverse stability is a well developed field with numerous contributors over many years. Techniques include simplified models and Vlasov equation analysis.
- For machines like SNS an accurate theoretical description of instabilities requires Mode Coupling Analysis because increments and tuneshifts are much larger than the synchrotron tune (200 versus 2000 turns).
- The incorporation of transverse wakefields into simulations was carried out by Blaskiewicz to study the head-tail instability with space charge. More recently, Danilov developed a transverse impedance formulation which has been implemented in ORBIT and UAL. Calculations with transverse impedances and space charge are very expensive because 3D space charge models are necessary to correctly describe the longitudinal dependence of the space charge force with oscillating beam centroids.
- Except for the 3D calculations by Ryne and Qiang, the simulations described so far were all carried out using, at most, 2D space charge models.

# Instability due to old Extraction Kicker Impedance




- Threshold – about $1.0 \times 10^{14}$ for zero chromaticity

  (for old extraction kicker impedance)
- Increment (for 2 MW) – about 200 turns
- Frequency range from 3-20 MHz
- Most unstable frequency – about 8 MHz
- Stabilized using
  - Active feedback (Danilov)
  - Octupoles (Fedotov)

# Electron Cloud Instabilities

- Transverse instabilities driven by clouds of ambient electrons have been observed in several proton (ISR, AGS, PSR, PS, SPS) and positron (KEK, CESR, KEKB, PEP-II) rings.
- Theoretical and computational work (Izawa, Rumolo, Zimmermann, Ohmi, Perevedentsev) has been done to analyze the observations for short bunches, which applies to most of these machines.
- However, PSR and SNS have long bunches and require independent analysis. Studies have been carried out for these machines using both coasting (Davidson, Qin) and bunched (Ohmi, Blaskiewicz, Wang, Macek) beam analysis.
- A number of computer models have been created to study the physics of electron clouds.

# Electron Cloud Codes

- For a complete simulation of the electron cloud physics, a code needs to include:
  - Electron generation / cloud formation (from residual gas ionization, emission from walls, or synchrotron radiation)
  - Electron tracking (external, self, and beam fields)
  - Beam tracking (external, self, and electron fields)
- A full PIC code simulation for a real ring (eg. PSR) will be computationally intensive, requiring dedicated massively parallel computing resources.

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## A survey of codes

| | Dim | Electron Model | Particle Pusher | Parallel (max cpu) | Fieldsolver |
|---|---|---|---|---|---|
| Quick-PIC, W. Mori et al. | 2-3 | | LeapFrog 4th order | YES(128), 32 regular | EM-PIC |
| CLOUDLAND, L.F. Wang | 2-3 | SE | Adaptive | NO | FEM |
| POSINST, M. Furman et al. | 2 | SR,RS,SE | RK | NO | Analytic |
| Head-Tail, Rumolo et al. | 2-3 | SR | Map | NO | PIC |
| Ecloud, Rumolo et al. | 2-3 | - | Leap Frog, Analytic | NO | Analytic,FFT |
| Warp, Friedman et al. | 3 | SR,RS,SE | | YES | ES-PIC |
| Orbit*, Holmes et al. | 3 | RG,SE, USER SPEC | Leap Frog, Analytic | YES | ES-PIC |
| Best, Qin et al. | | | | NO | DeltaF |
| Vlasov, Novokhatski et al. | | | | NO | |
| PARSEC*, Adelmann et al. | 3 | SR,RS,SE | RK-x,Analytic | YES (4096) | FEM MG ES |
| CSEC etc. Blaskiewicz | | | Symplectic | NO | Analytic |
| CMEE, Stoltz | Library for computational methods for electron cloud effects | | | | |

**Courtesy of Andreas Adelmann**

SR: Synchrotron Rad
RS: Residual gas scattering
SE: Secondary emission
*: not for production runs yet

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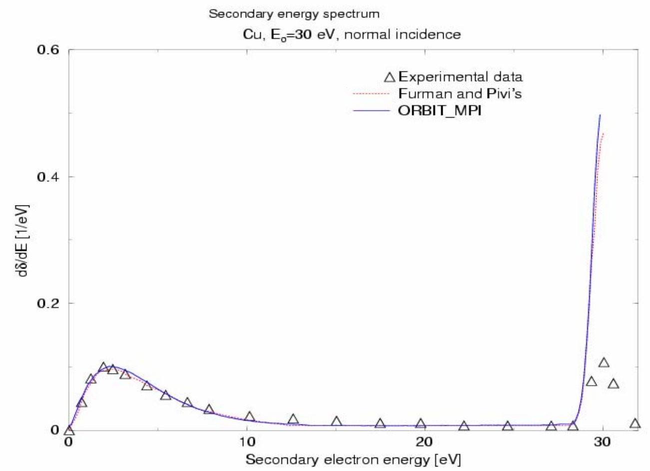
# Electron Cloud Formation

- Detailed phenomenological models of electron sources have been developed by Pivi and Furman. Their secondary emission model includes elastic scattering, rediffusion, and true secondary emission as functions of incident electron energy and angle for a variety of surface materials.

- In PSR, electrons are trapped in the first, rising current, part of the pulse and escape to strike the walls and enhance the cloud through secondary emission at the bunch tail.



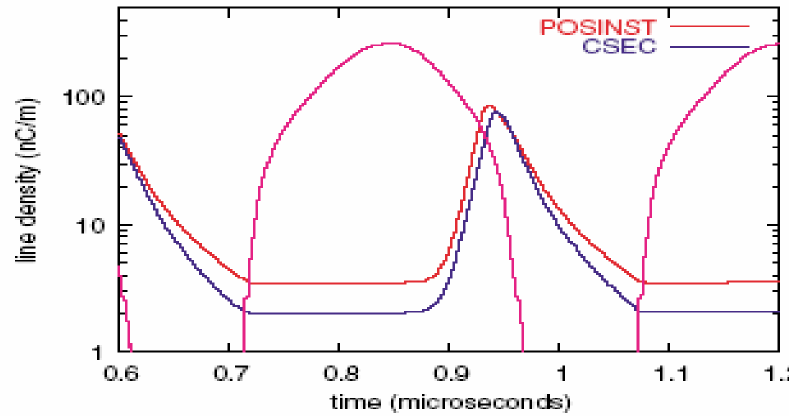
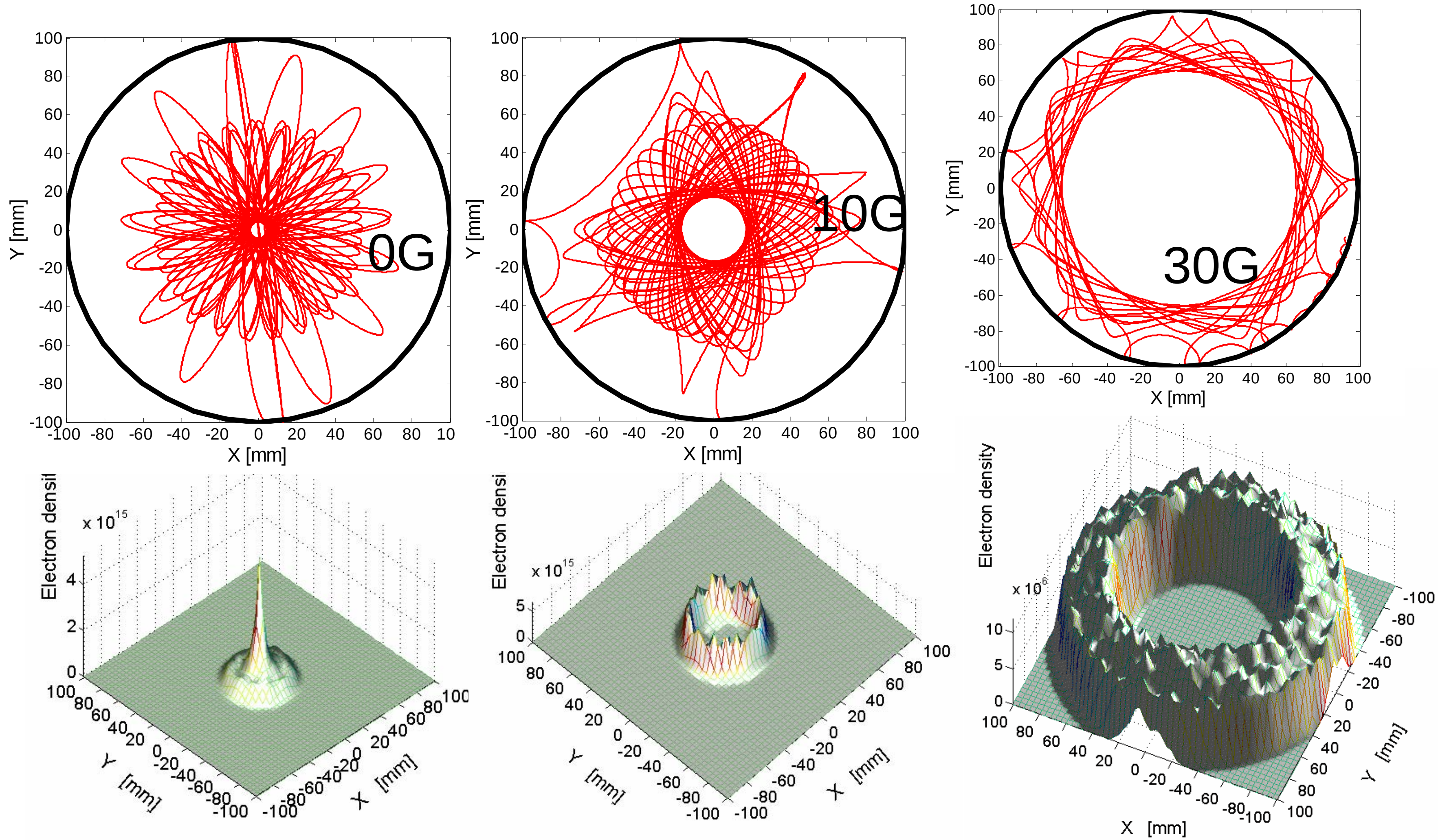




FIG. 6. (Color) Beam line density (purple) and total electron cloud line densities for the PSR obtained with CSEC (blue) and POSINST (red).

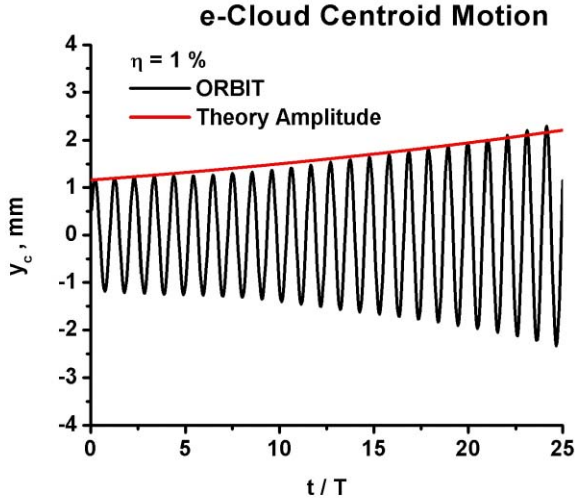
# Electron Tracking: Solenoid effects

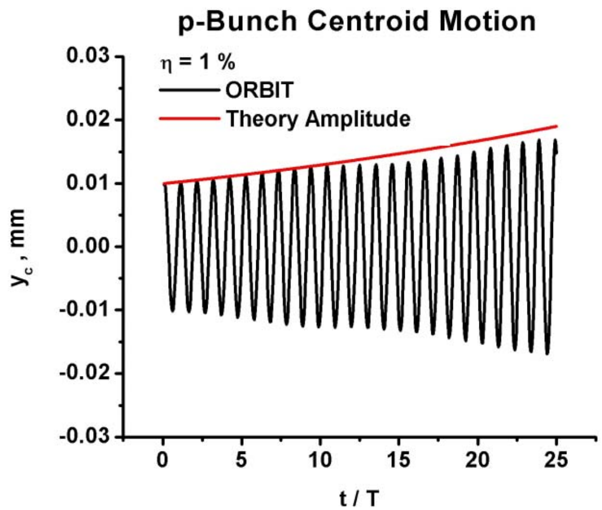
(L. Wang, J. Wei, M. Blaskiewicz, et al)

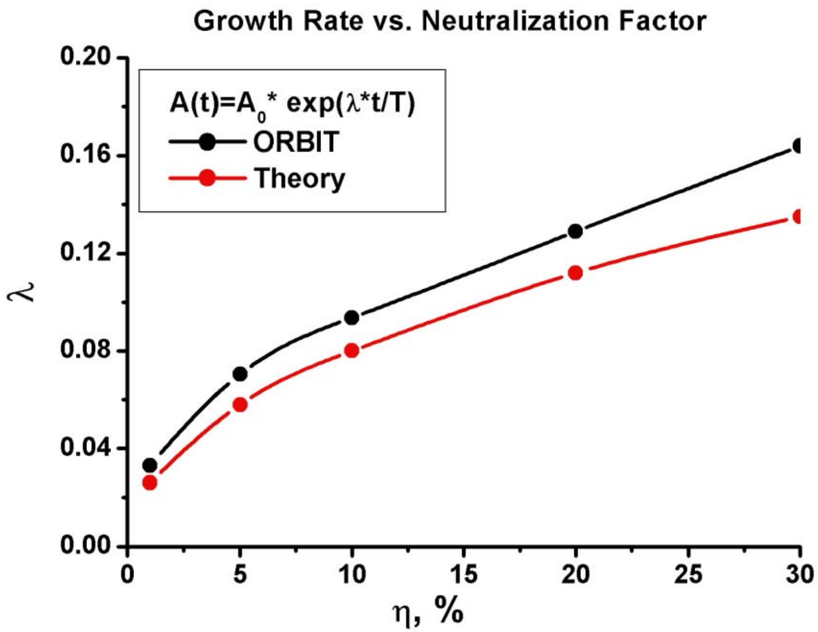
- **30G Solenoid field can reduce the e-cloud density with a factor 2000 !**
- **Solenoid in the collimator straight section**



# Two stream benchmark of ORBIT with Analytic Model due to Neuffer



# Self Sustaining Bunched Space Charge Distributions

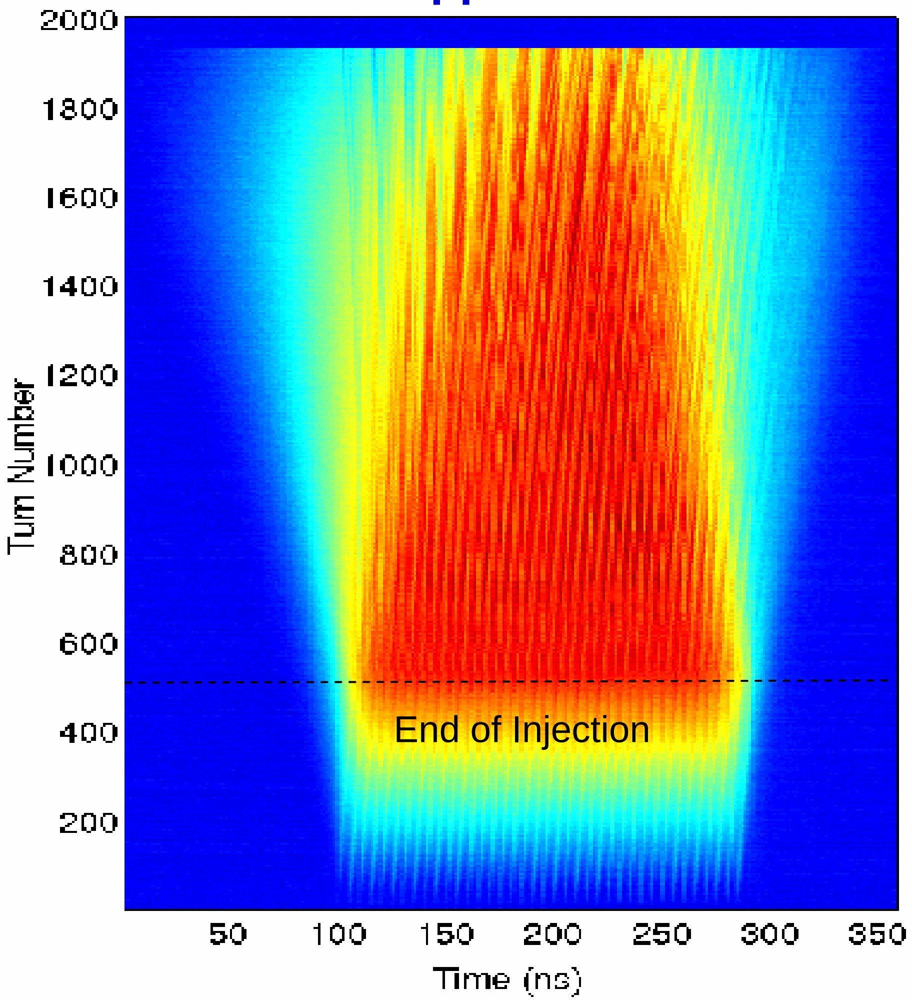
- Stationary longitudinal bumps and holes have been observed in a number of accelerators including the CERN PSB, SPS, and Tevatron.
- Schamel showed that such solitons can not be predicted using linearized Vlasov analysis.
- Recently, Koscielniak has derived conditions for the existence of stationary holes maintained by space charge in a longitudinal Hamiltonian system; and Blaskiewicz has demonstrated that a defocusing impedance can support humps in bunched beams, as observed in RHIC.
- The following presents a clear illustration of a self sustaining bunched space charge distribution observed in PSR. Key to observing this phenomena are the facts that the linac injection frequency is a multiple (72) of the ring frequency and that the ring RF focusing was turned off.

# The PSR 201 MHz Phenomenon

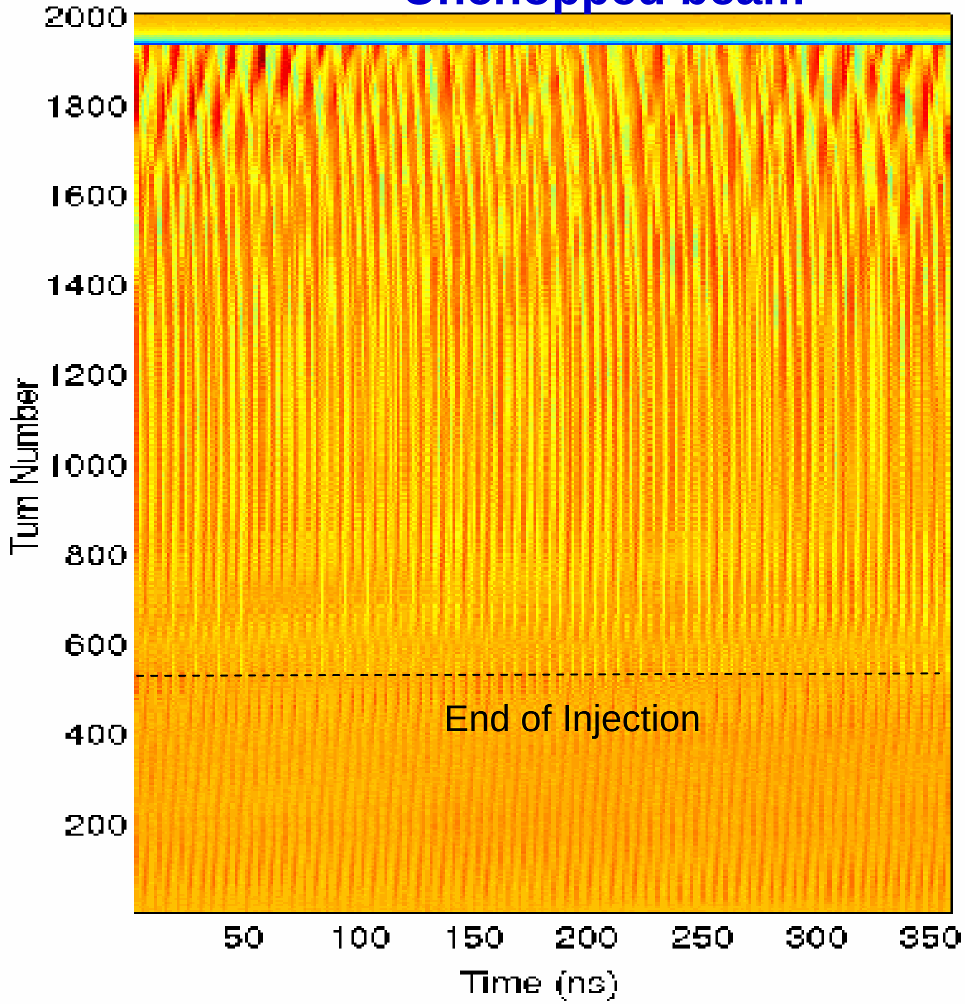
**(Cousineau, Holmes, Danilov)**

- 201 MHz structure in PSR should disappear in ≈ 30 turns (no RF bunching)
- Microwave instability data shows this structure persists for ~1000 turns.

**Chopped beam**

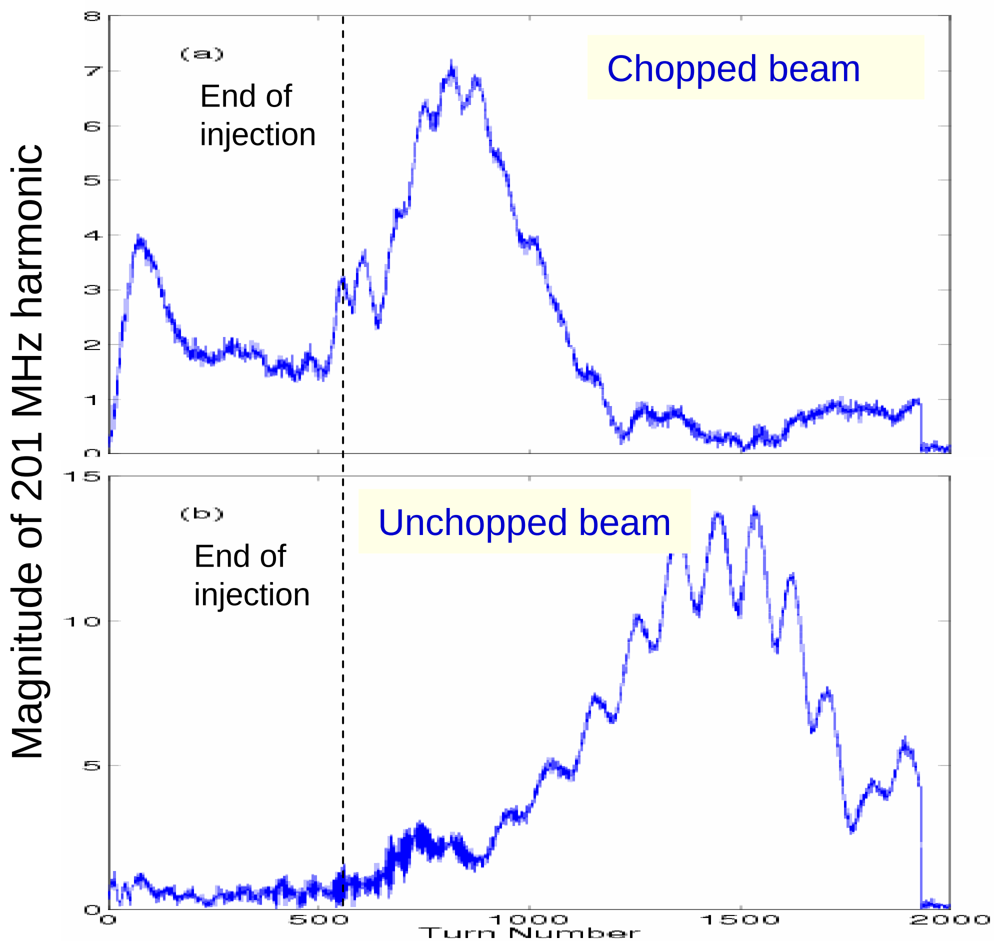



**Unchopped beam**

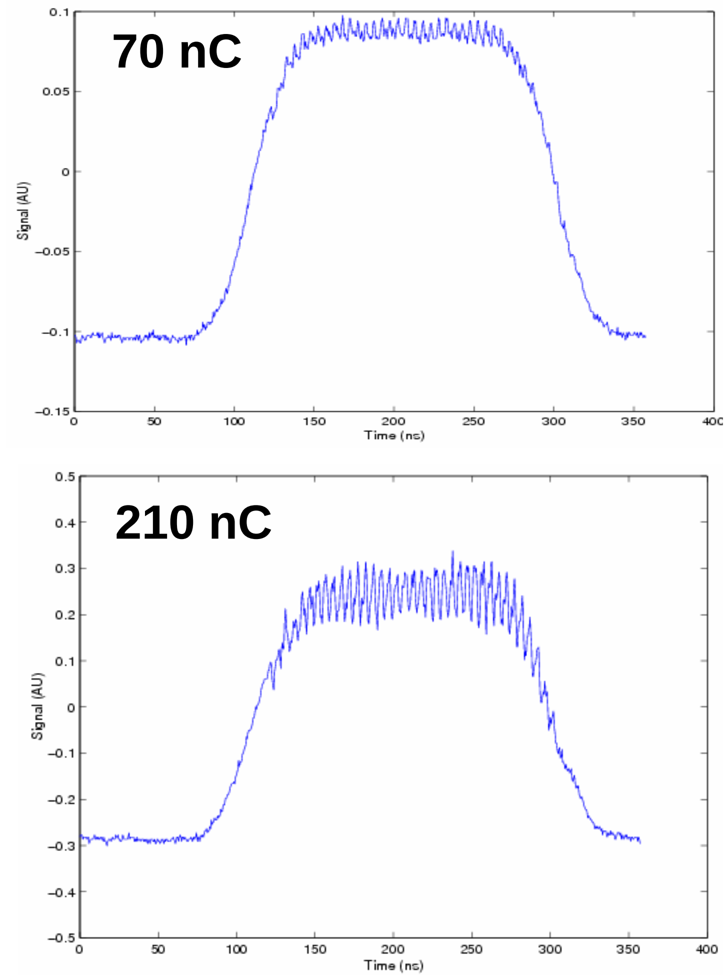


# Experimental Analysis of the 201 MHz Structure

- Analysis of 201 MHz harmonic shows structure increasing after injection.
- Analysis also shows 201 MHz structure is stronger at higher intensity

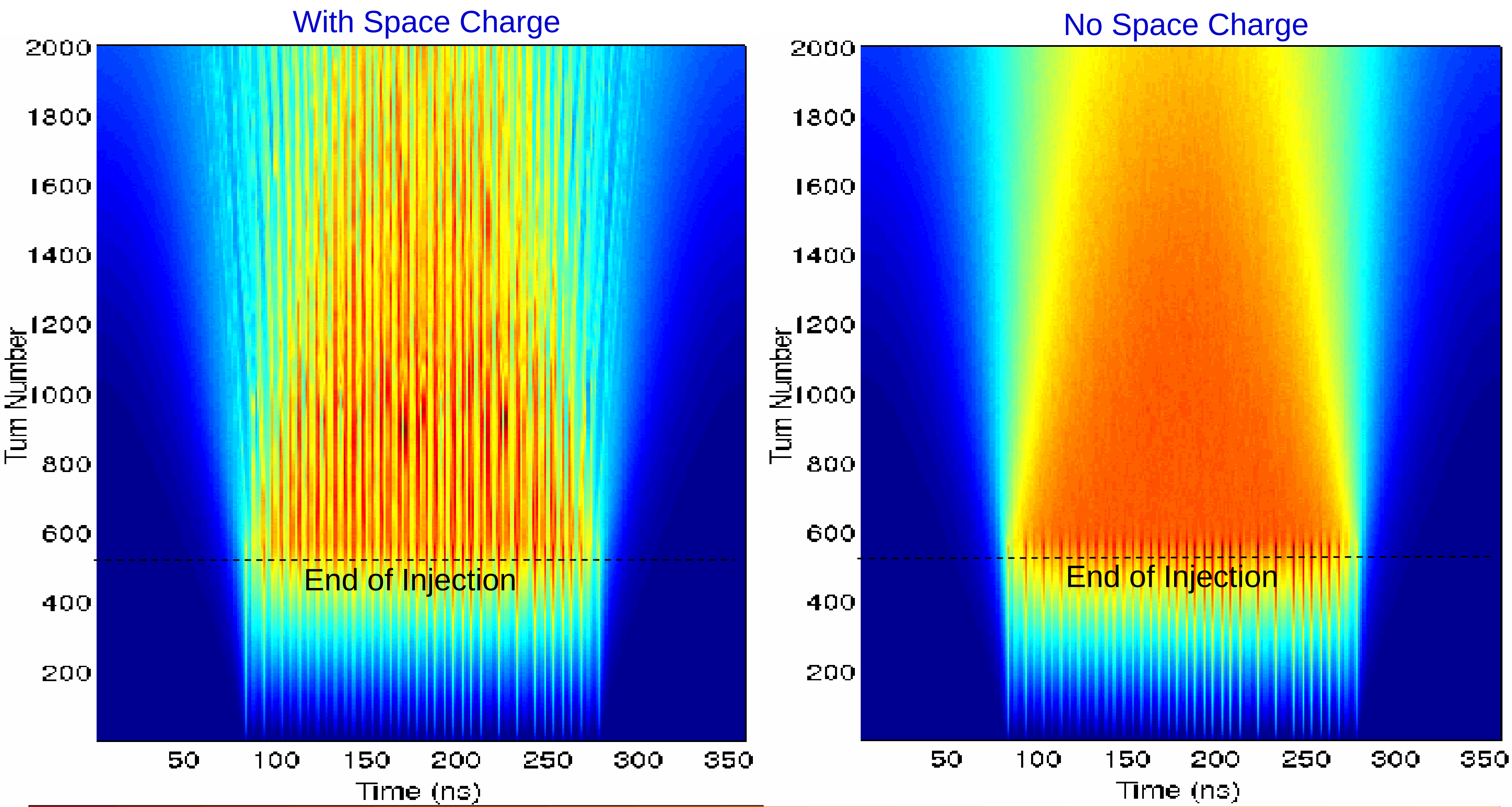



Longitudinal profile 300 turns after end of injection for chopped beam.



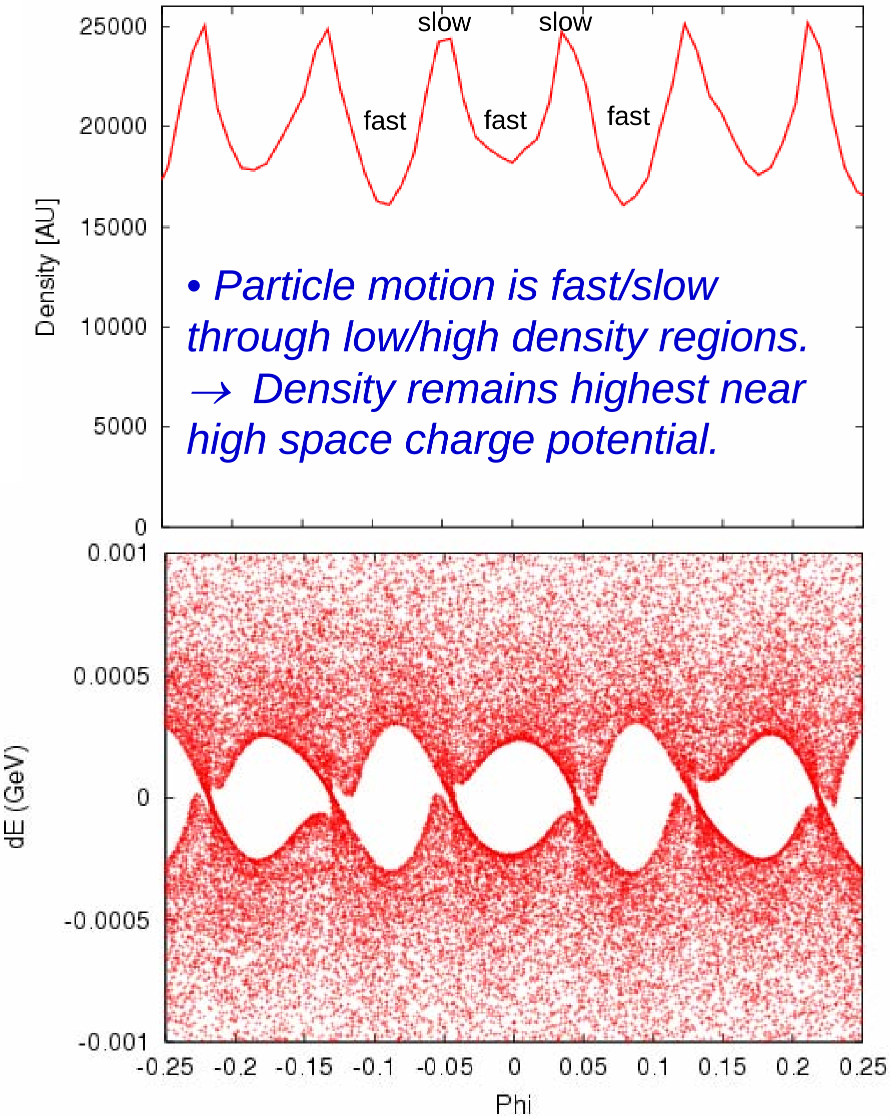
# Simulations of the 201 MHz Structure

- 1D tracking simulations with ORBIT show same long-lived 201 MHz microstructure; structure present with or without impedance.
- Structure quickly decoheres in simulations without space charge.



# Formation of Empty Phase Space Buckets

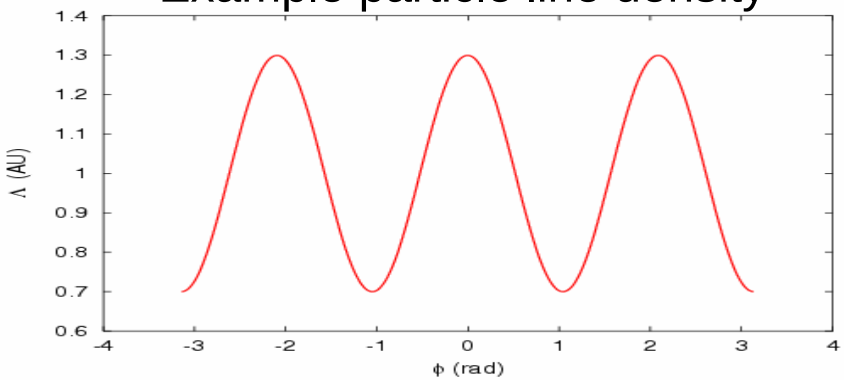
- Protons are injected with energy spread at the same locations, turn after turn, thus reinforcing the distribution.
- As the particles move longitudinally, they accelerate away from the density peaks, moving quickly across the density holes and slowly near the peaks.
- This motion acts, for a range of beam intensities, energy spreads, and injection rates, to sustain the distribution.
- In one numerical experiment for a 1000nC injected beam, the structure persisted for 10000 turns, when the calculation was stopped.



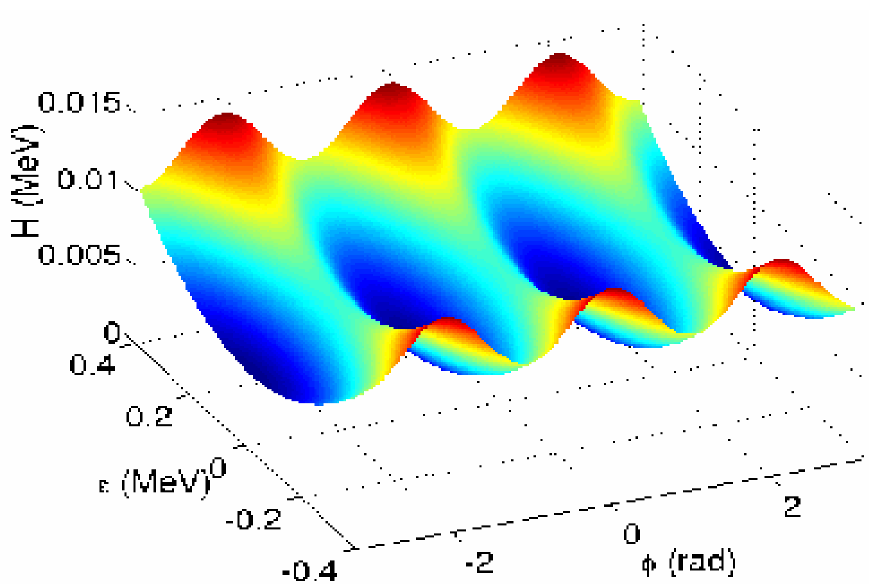
# Observations of 201 MHz Structure Dynamics

- Self-consistent, steady-state solutions can be found for a range of periodic potentials. Solutions constrained to narrow band in Hamiltonian space.
- Maximum particle density occurs outside of separatrix.

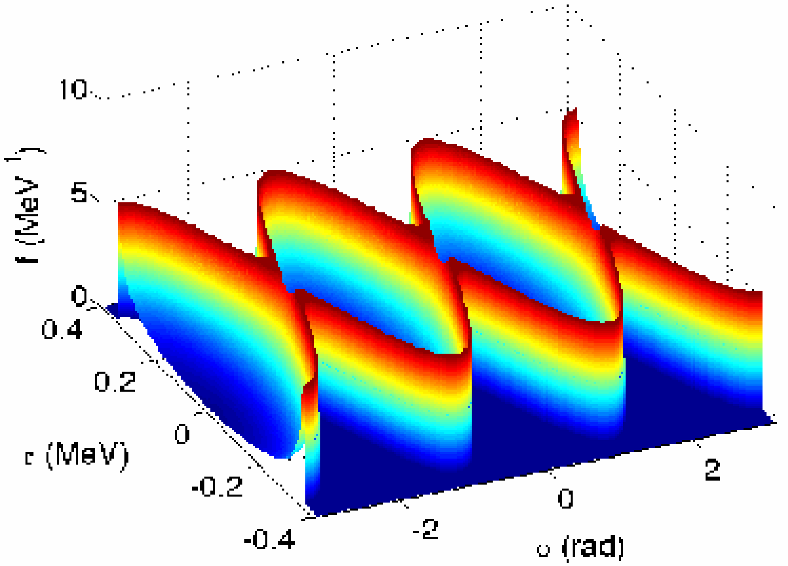
Example particle line density




Steady-state Hamiltonian surface




Steady-state distribution function



# Conclusion

- Computer simulation techniques, utilized in conjunction with theory and experiment, are providing invaluable analytic, visualization, and verification capabilities in the study of high intensity collective beam dynamics.
- One of the big advantages of computer simulation is the degree of control provided. It is possible to regulate calculations and to obtain diagnostic information with machine precision.
- With the increasing detail and sophistication of contemporary computer models, it is now possible to mimic many accelerator experiments and their physics with surprising precision.