Cyclotron Resonances in Electron Cloud Dynamics*

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E- Cloud Effects are Predicted to Be Severe in the ILC Positron Damping Ring

Beam current is very high ⇒ lots of synchrotron emission

Simulations predict:

Without any mitigations, cloud density high enough to cause beam instability and other effects.

Mitigations:

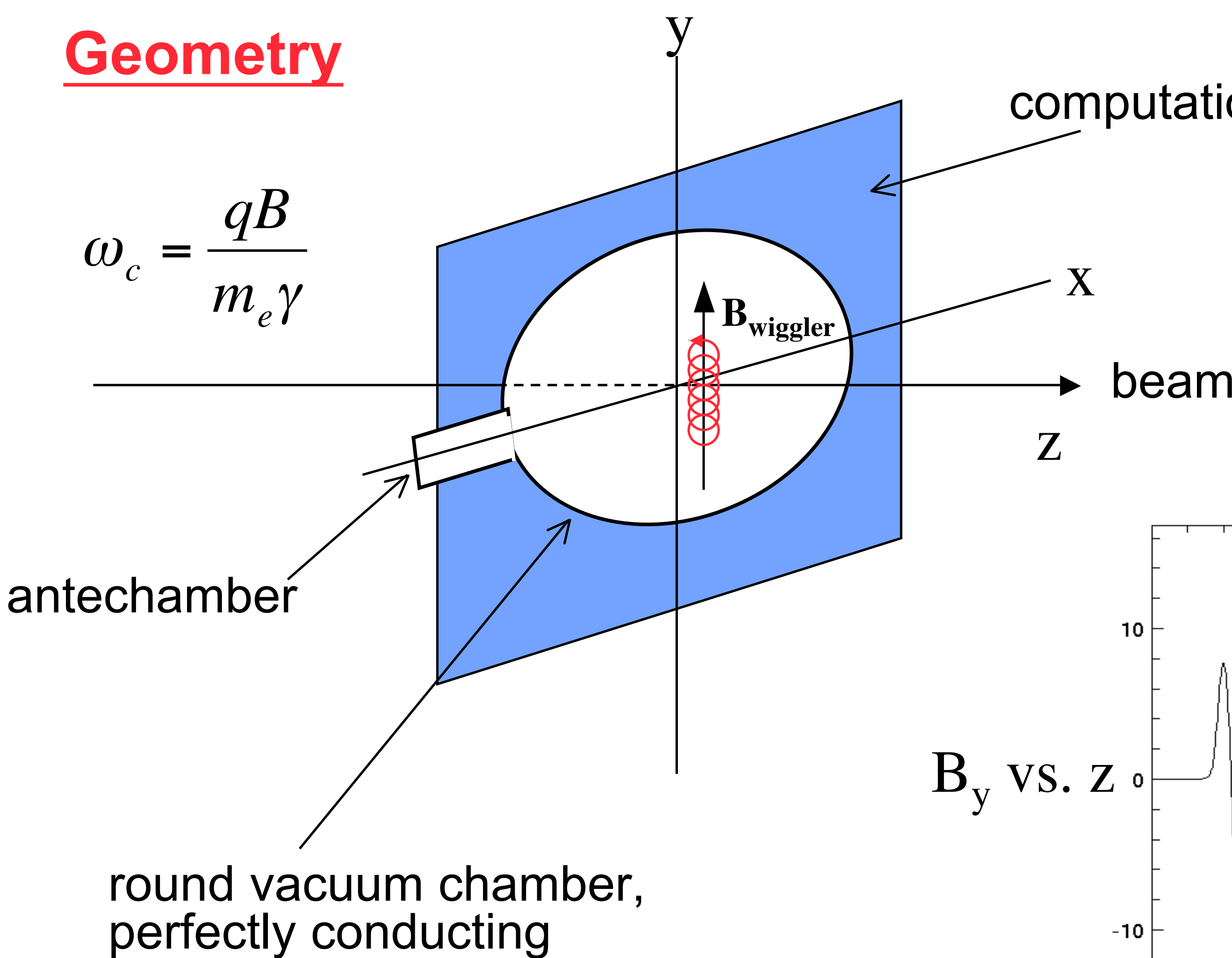
Wall treatments are planned, to reduce the secondary electron emission.

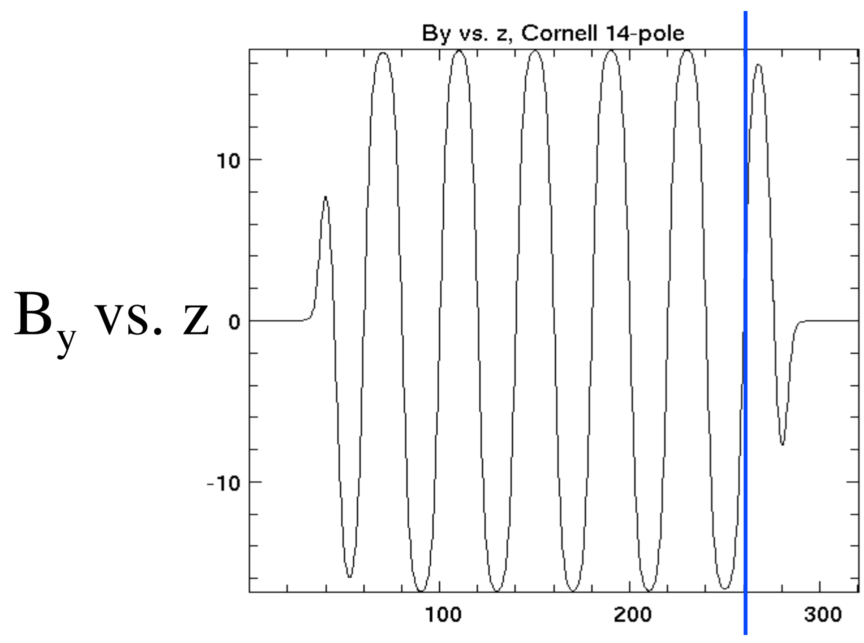
We are interested in simulations of the wiggler electron cloud buildup-- experiments now in progress at CesrTA

POSINST, a 2D Computer Code, was used to Simulate x-y Slices of the Wiggler

Geometry

$$\omega_c = \frac{qB}{m_e \gamma}$$





POSINST uses certain assumptions...

- Beam does not evolve in time (OK for short times, e.g., buildup)
- Beam electric field is transverse only (relativity)
- Beam magnetic field neglected   (v_e small)
- Electrons generated according to phenomenological models
  secondaries: Furman-Pivi*

The force of the electrons on each other as it evolves in time is calculated self-consistently by a **Particle-in-Cell** algorithm.

*M.A. Furman and M.T.F. Pivi, PRST-AB **5**, 124404 (2002)

Cloud Buildup Calculations were done using ILC Damping Ring Parameters

"Wiggler":

$B_y \leq 1.6$ T; $B_x = B_z = 0$ (ideal dipole)

Vacuum Chamber:

R = 2.3 cm (vacuum chamber radius)

Antechamber full height = 1 cm

Beam:

2×10^{10} e+ per bunch

9 GeV

$\sigma_x = 0.112$ mm, $\sigma_y = 4.6$ μm, $\sigma_z = 6$ mm

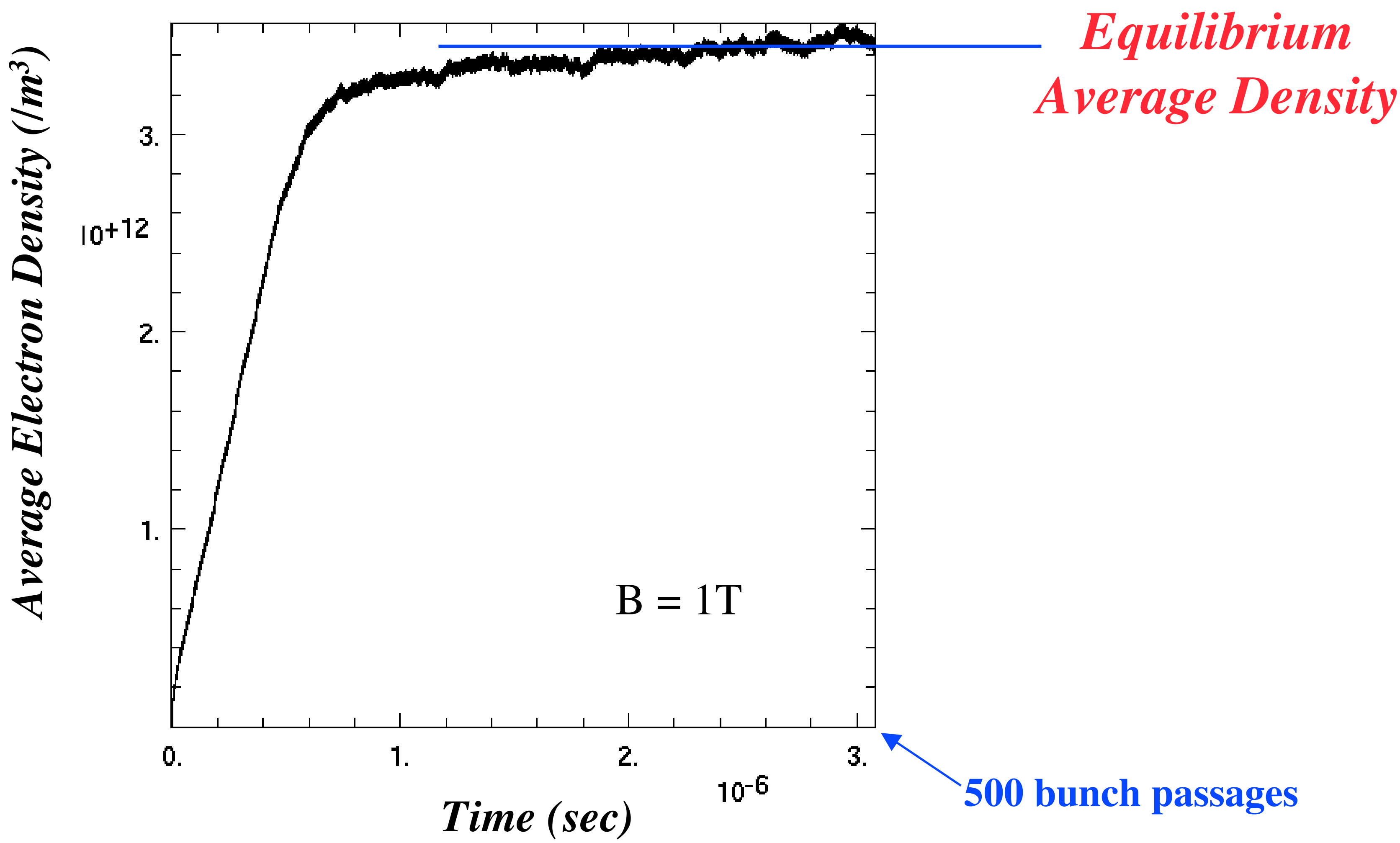
bunch spacing: 6.15 ns

Electron Production:

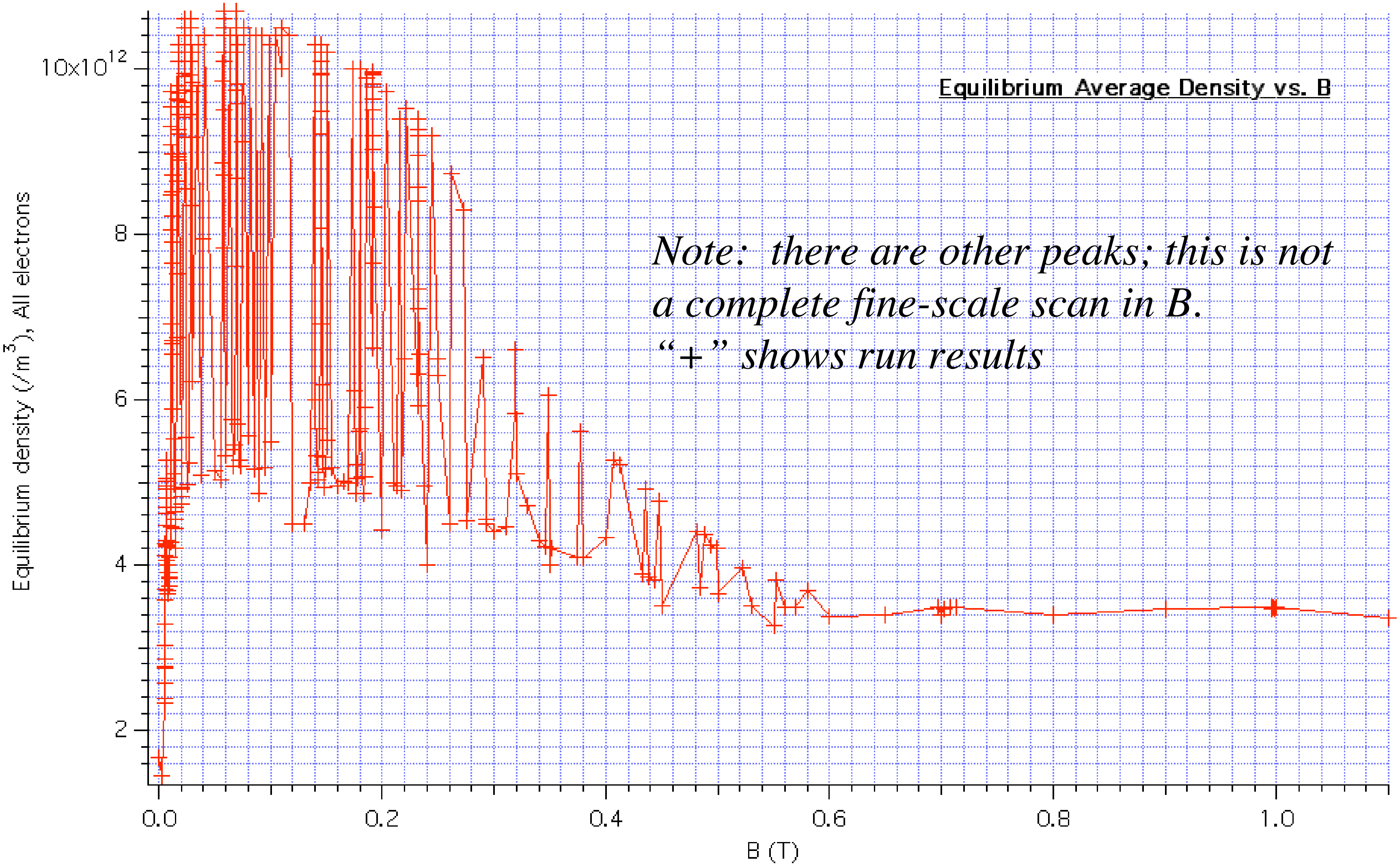
photon reflectivity = 1

peak SEY @ normal incidence = 1.4

For a Given B, the Average Electron Density Builds Up over Time, then Plateaus



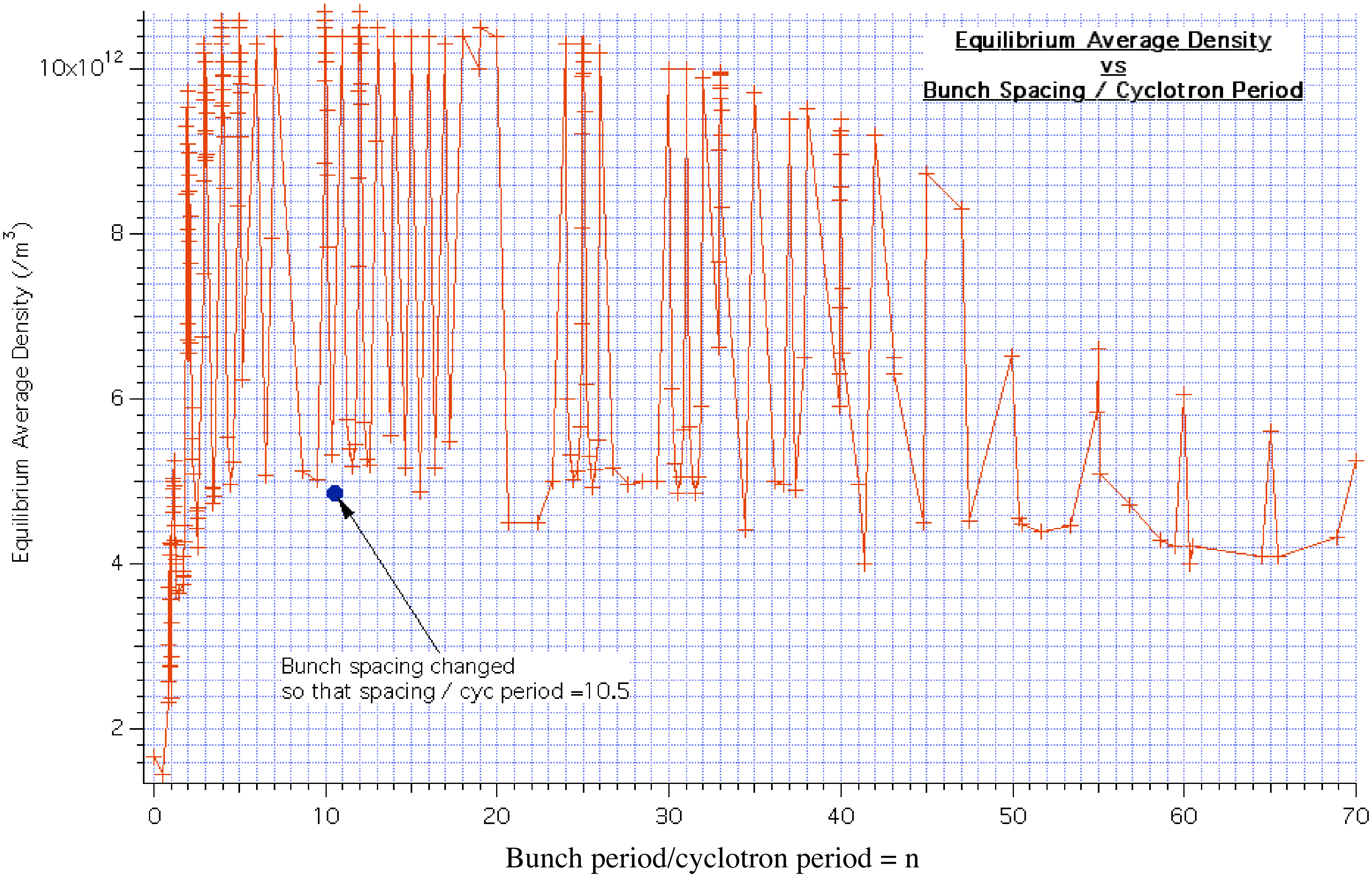
Average Equilibrium Density vs. B has Peaks at Low B!



Density at peaks is up to 3x its value at high B.

Peaks all fall on Integral Values

Note: some peaks (and dips) missing because runs have not yet been done at that field



Explanation: Appears to be resonance between bunch passage & cylotron motion

If:

$$\frac{\omega_c}{\omega_b} = n$$

ω_c = qB/m = cyclotron frequency, ω_b = bunch frequency

Then:

Each time the electron gets a push from the beam field, it is in the same position ⇒ **Resonance**

Important:

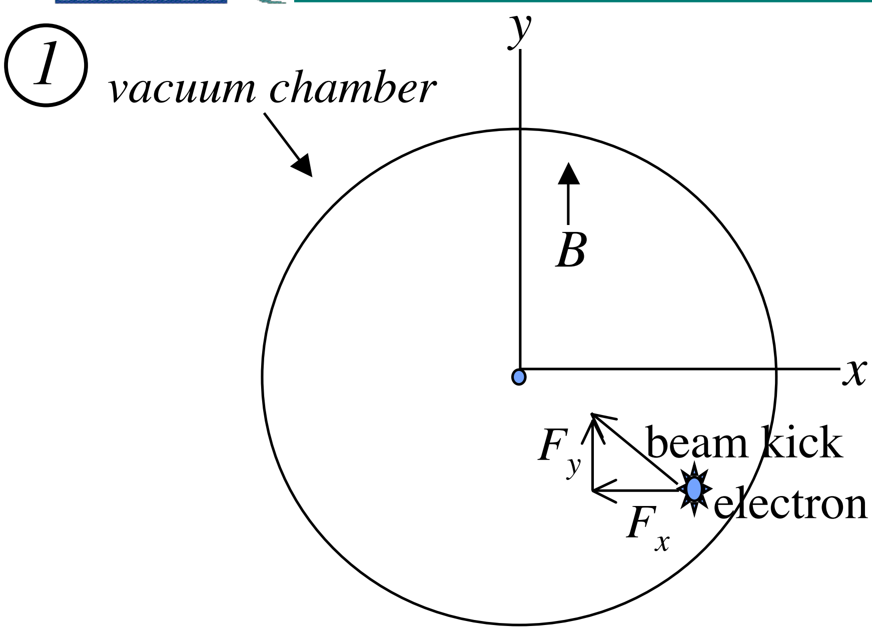
Cyclotron frequency is function only of B for v<<c.

$$\omega_c = \frac{qB}{m_0 \gamma}$$

γ = relativistic factor

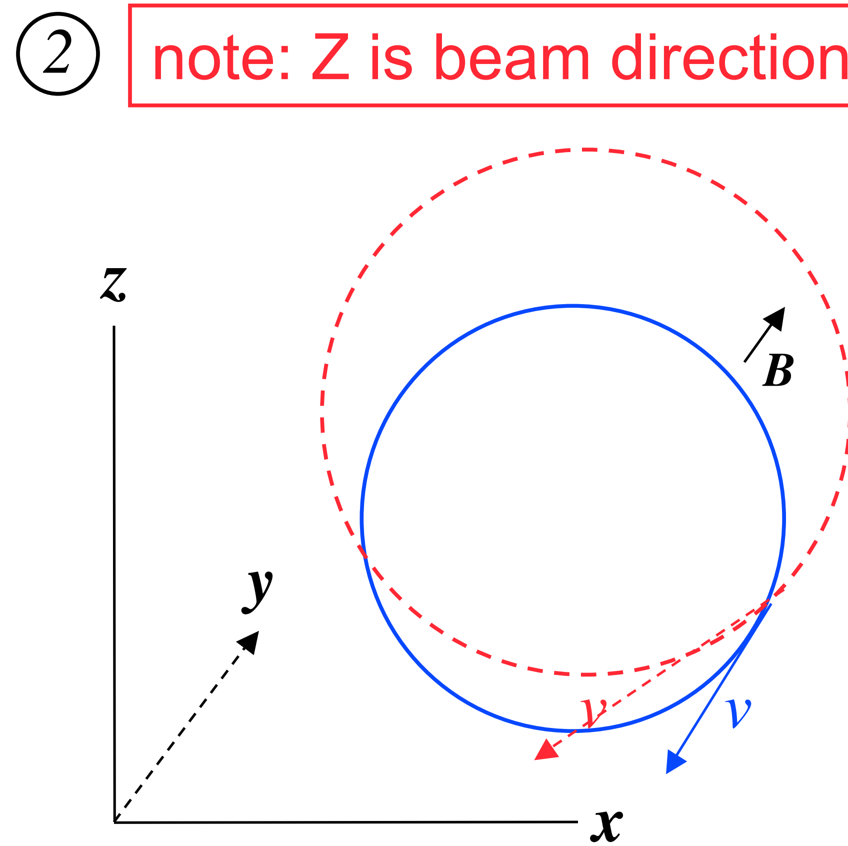
So electron stays in resonance until detuned by relativistic mass increase or space charge.

How it Works



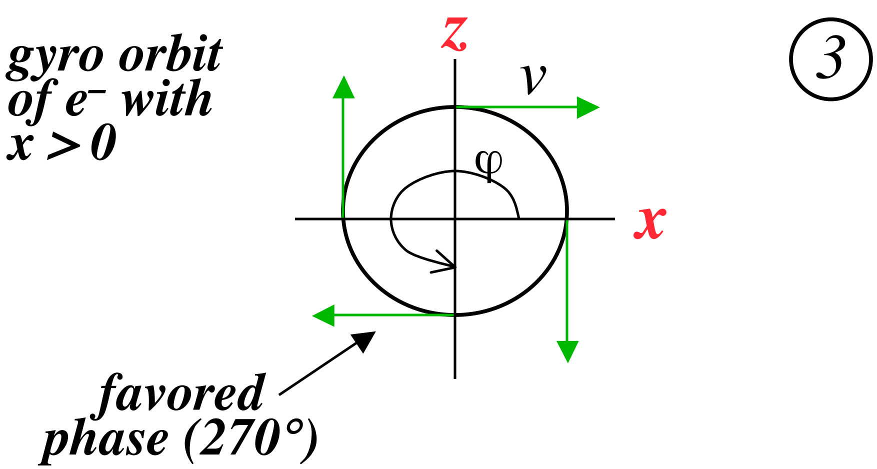
F_x is always toward the center

note: Z is beam direction



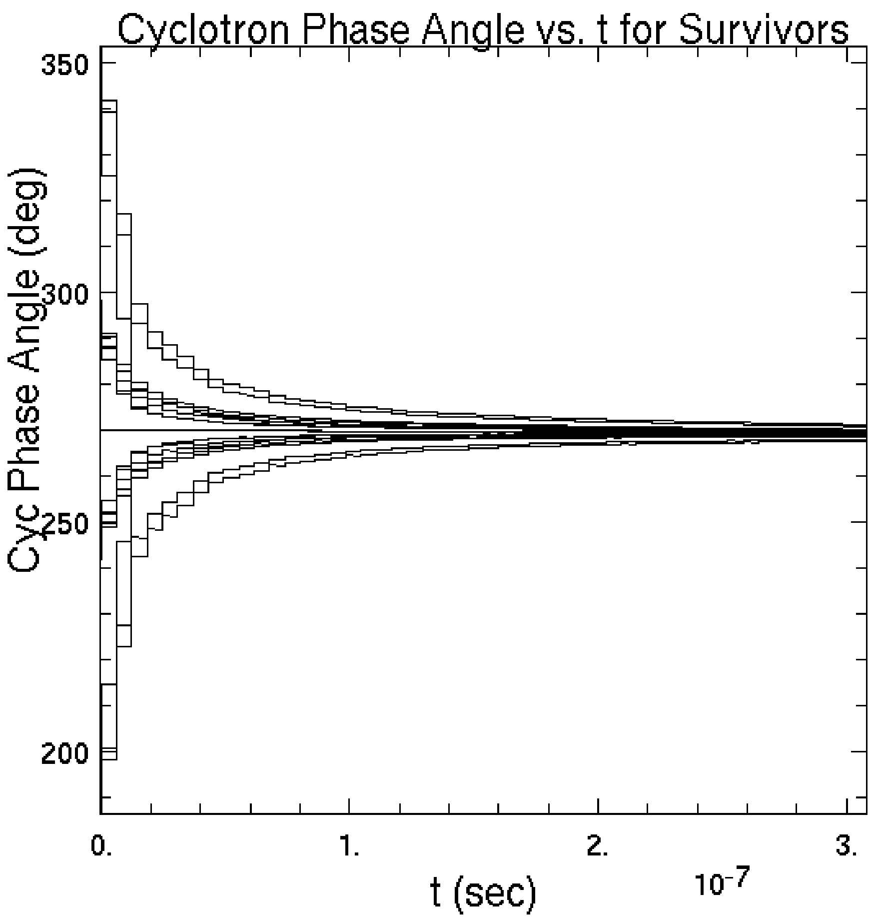
– *before beam kick*

– *after beam kick*

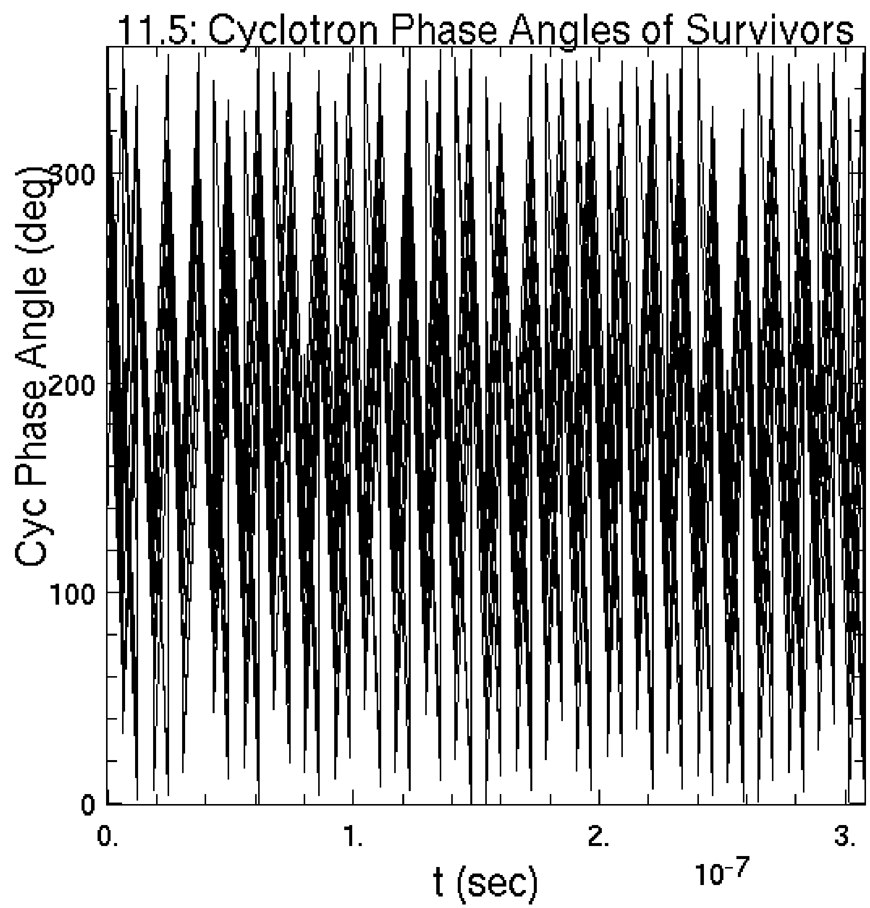


A single particle model shows phase angles coelescing at resonance

n=12 (resonant case)

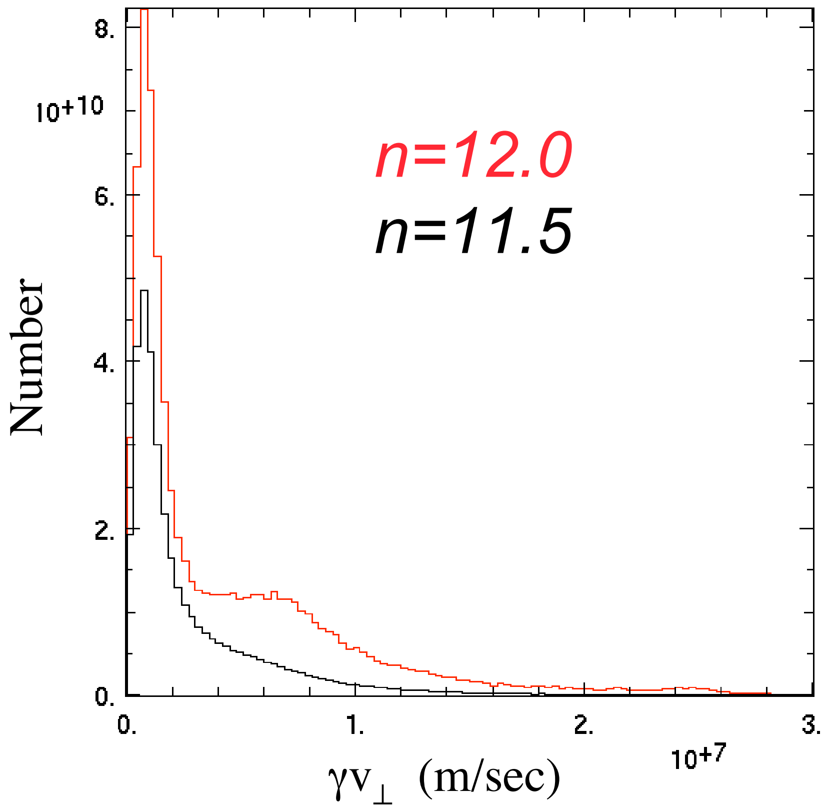


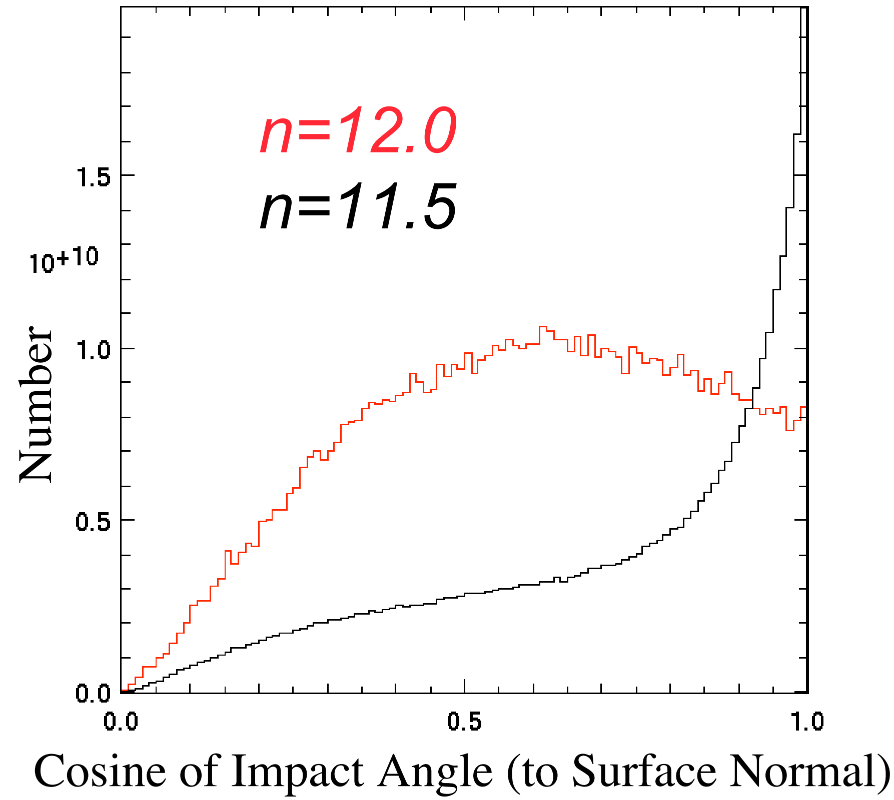
n=11.5 (nonresonant)



Cyclotron phase angle goes to 270°, as predicted, for resonant case, but not for nonresonant.

POSINST, as well as single particle model, shows increased $v_\perp$ and impact angle

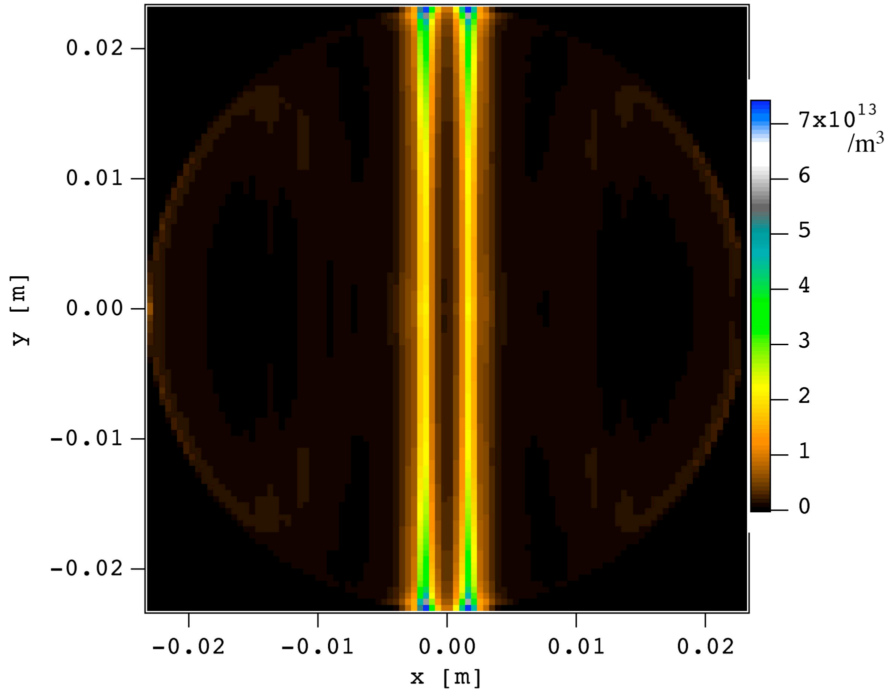




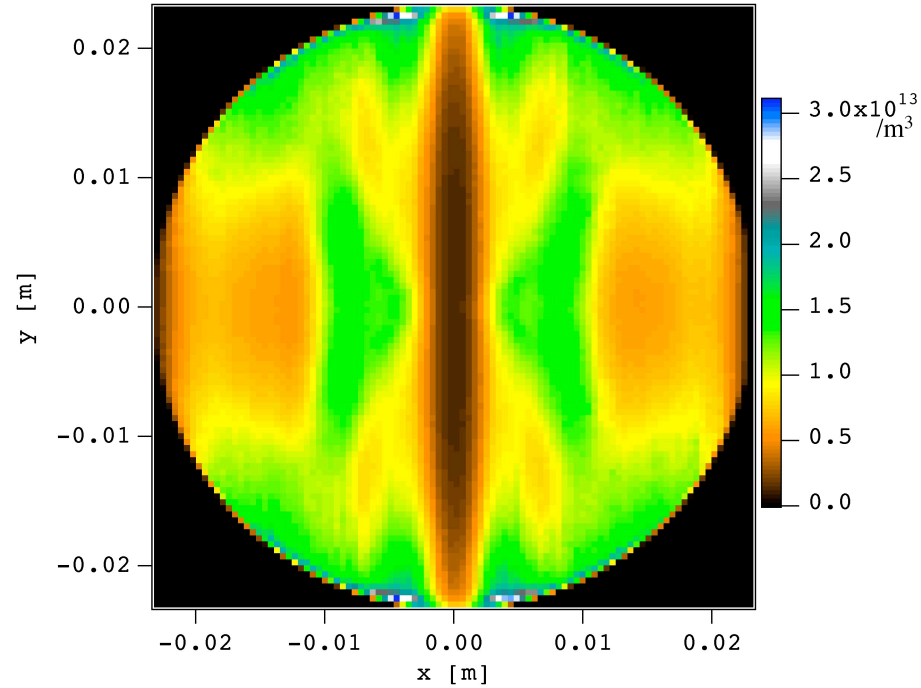
Both of these effects cause an increased secondary electron yield

Another effect, from POSINST Simulation: Electrons more Dispersed in Resonant Case

Density Distribution Averaged over Run (POSINST) X-Y Plane

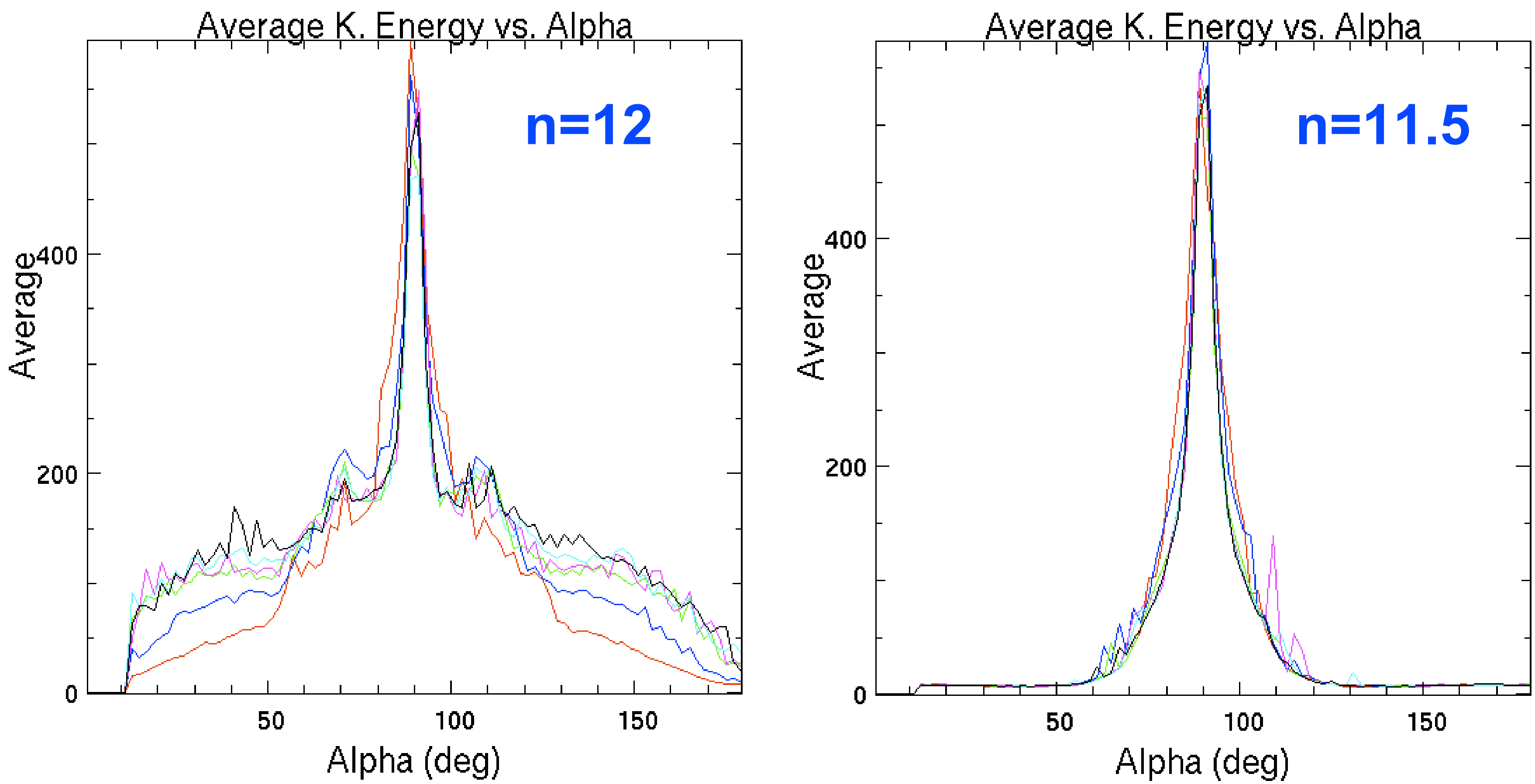


Non-resonant B



Resonant B

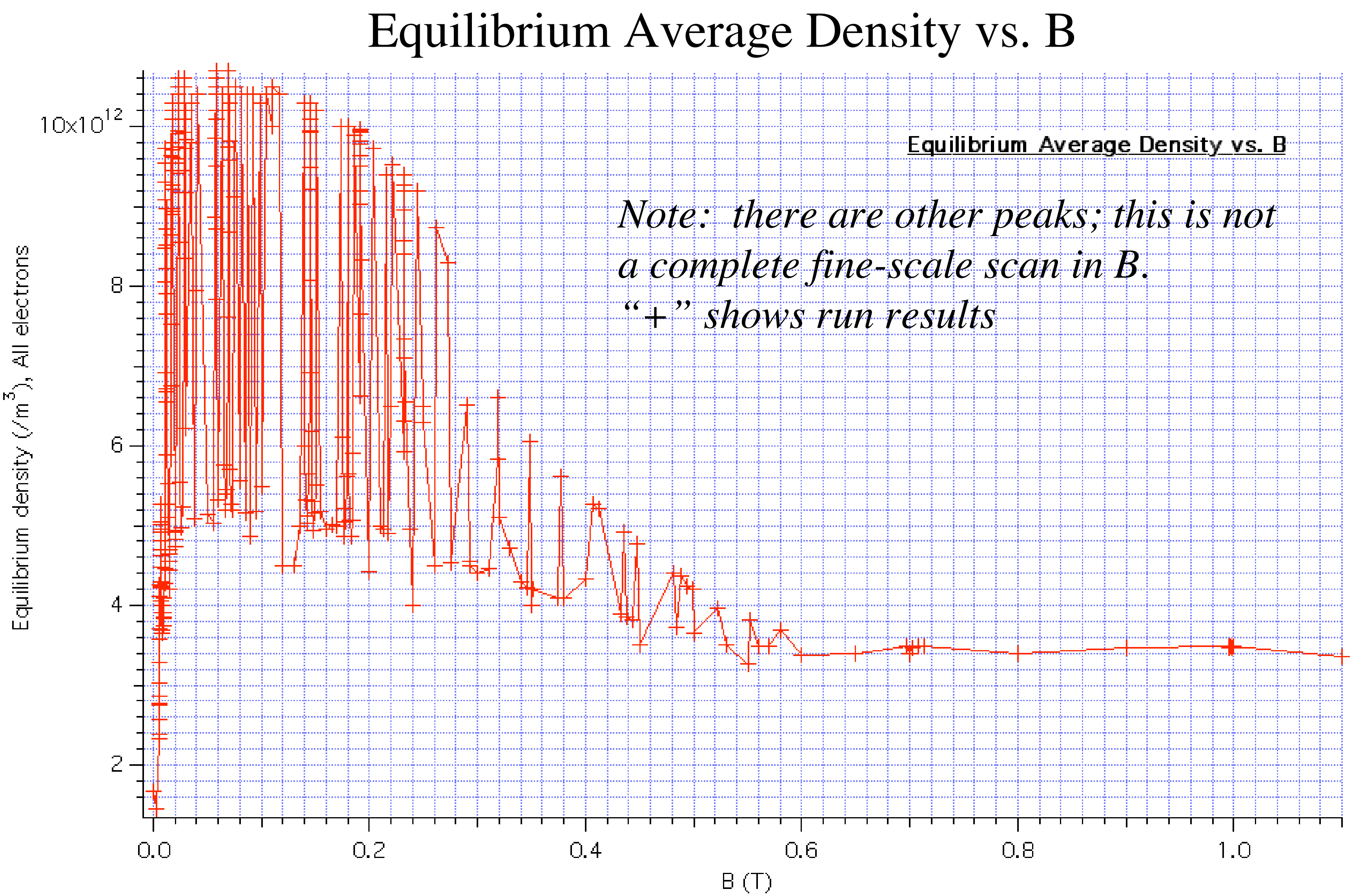
Explanation: At resonance, electrons over a much bigger area have 100 - 200 eV



At resonance there is an additional method of adding energy-- the beam E_x can be effective, not just E_y. This changes the locations where electrons feel the greatest effect from the beam.

Why do resonance effects disappear at high B?

Peaks Disappear as B Increases



If the bunch is too long or B too high, the electron moves during the beam passage

As B increases, cyclotron period decreases

l_b=bunch length

$$\tau_c \Rightarrow l_b/c$$

Beam force now integrates over cyclotron period as $v_\perp$ direction changes.

$\Rightarrow$ very little effect*

Resonance only effective if $\tau_c >> l_b/c$, or

$$B \le 2\pi \frac{m_0 c}{q l_b}$$

This probably is the reason that the resonance was not noted before--calculations were done for longer bunches and higher fields.

* effect mentioned in different context in Furman and Lambertson, LBNL-41123, 1998

Results of a Simple Analytical Model are Illuminating

Assumptions:

- Beam kick is always that for electron's position at t=0
  - Appropriate for portion of electrons' phase space (not near x=0, y-amplitude small)
- Electrons don't hit wall, i.e.:
  - Short time
  - $\rho_0 < R_{chamber}$ (so B not very small)

Model:

$$\lambda(z,t) = eN_b \sum_{k=0}^{\infty} \frac{e^{-(z-ct+kc\tau_b)^2/2\sigma_z^2}}{\sqrt{2\pi}\sigma_z}$$

Positron beam line density

$$\mathbf{E}(x,y,z,t) = \frac{\lambda(z,t)}{4\pi\epsilon_0}\vec{\mathcal{E}}(x,y)$$

E-field from positron beam

$\vec{\mathcal{E}}(x,y)$ = 2D Bassetti-Erskine field

Equations of Motion:

$$\dot{v}_x = -(e/m_e)(E_x - v_z B)$$
$$\dot{v}_y = -(e/m_e)E_y$$
$$\dot{v}_z = -(e/m_e)v_x B$$

Eqs. of motion for a single electron (assumed nonrelativistic)

And solve ...

Solve to first order in λ:

$$\ddot{v}_z + \omega^2 v_z = \frac{\omega^2 E_x}{B} = \frac{eN_b\omega^2\mathcal{E}_x(x,y)}{4\pi\epsilon_0 B}\sum_{k=0}^{\infty}\frac{e^{-(z-ct+kc\tau_b)^2/2\sigma_z^2}}{\sqrt{2\pi}\sigma_z}$$

Take d/dt of #3 above and combine with #1

$$\ddot{v}_z + \omega^2 v_z \simeq \frac{eN_b\omega^2\mathcal{E}_x(x_0,y_0)}{4\pi\epsilon_0 Bc}\sum_{k=0}^{\infty}\frac{e^{-(t-k\tau_b)^2/2\sigma_t^2}}{\sqrt{2\pi}\sigma_t}$$

Solution:

$$v_z(t) \simeq -\omega\rho_0\sin(\omega t+\phi_0) + \kappa\theta(t)N_b r_e c\mathcal{E}_x(x_0,y_0)A(K,n)\sin(\omega t-\pi nK)$$

$$\kappa = e^{-(\omega\sigma_t)^2/2}, \qquad n = \frac{\omega\tau_b}{2\pi}, \qquad A(K,n) = \frac{\sin(\pi n(K+1))}{\sin(\pi n)}$$

$K \equiv \lfloor t/\tau_b \rfloor$ is the largest integer $\leq t/\tau_b$.

exponential falloff of effect as cyclotron period ⇒ beam extent in time

Simple analytic approach - 2

Can then obtain solutions for $v_x(t)$, $x(t)$ and $z(t)$. Also $y(t)$, but for this intensity electrons hit the wall in a few bunch passages.

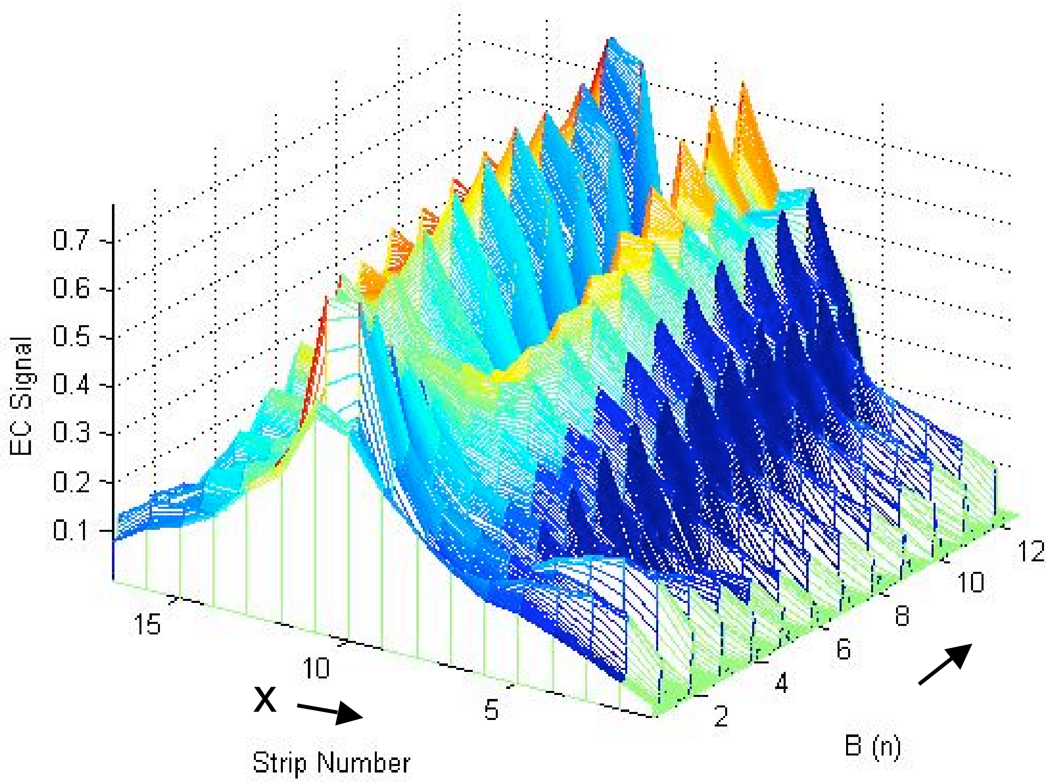
Results:

Equations show that:

- Amplitude and energy grow on resonance (n=integer, because then A(K,n) grows in time)
- For n=integer, electrons soon "forget" their initial conditions & become synchronized with the beam
- If $n \neq$ integer, no amplitude growth
- Resonance suppressed by exponential factor when $\omega\sigma_t \geq 1$

The Resonances were seen in the electron cloud experiment at PEP-II

Dipole field strength dependence



$$n = \frac{\text{bunch spacing in time}}{\text{electron cyclotron period}}$$

Electron flux peaks (and valleys) separated by integer values of n.

Phase of cyclotron motion with respect to bunch crossing affects energy gain, possibly leading to the observed modulation in electron flux at the chamber wall.

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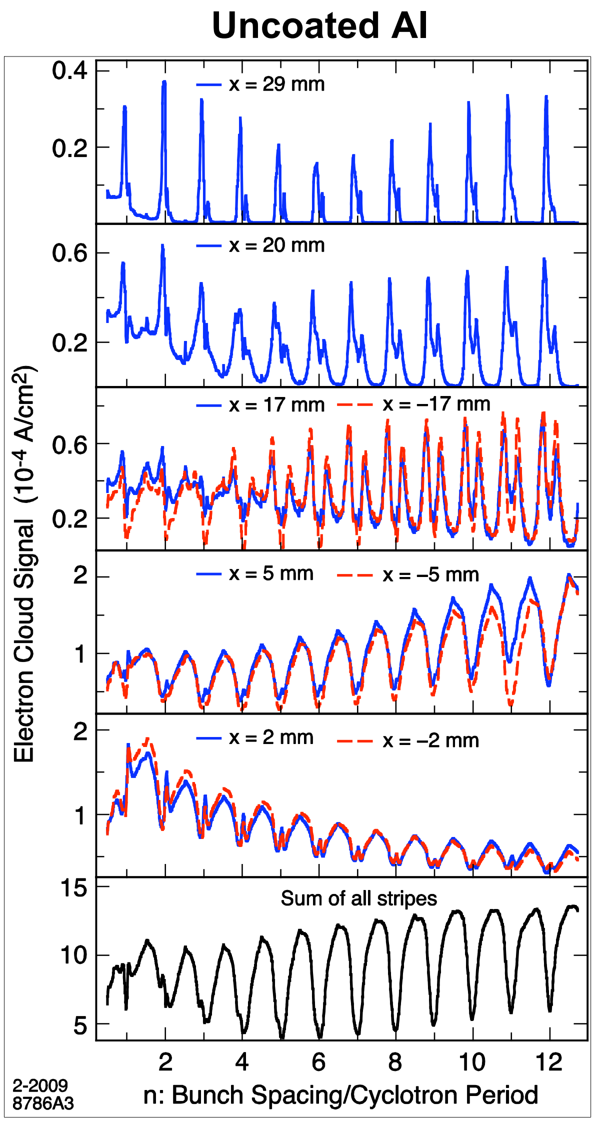
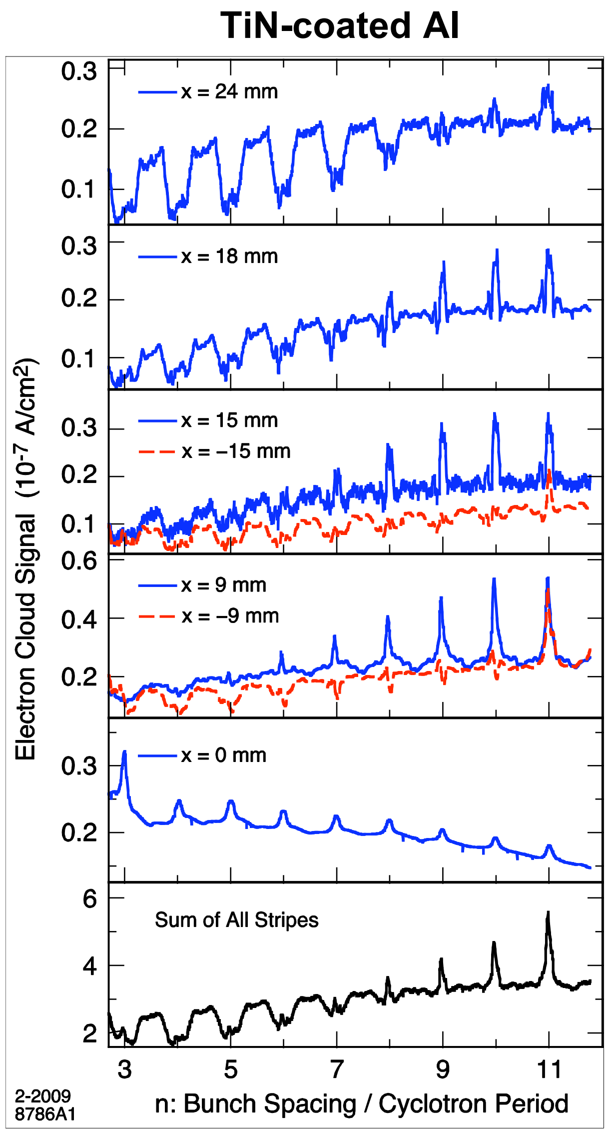
Observation of Cyclotron Resonances at PEP-II

[M.T.F. Pivi and J.S.T. Ng, *et al.* SLAC-PUB-13555, Mar. 2009]





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Conclusions

1. When the bunch period is an integral multiple of the cyclotron period, a resonance occurs. If the electrons stay in the system long enough, their $v_\perp$ increases until the relativistic mass increase detunes them from resonance.

2. For our parameters most electrons strike the wall after a few bunch passages, but the resonance causes a significant change in $v_\perp$ and in the cloud density.

3. When the time for the bunch to pass is comparable to the cyclotron period (long bunches or high B) the effect averages over the cyclotron oscillation and washes out-- no increase in density.

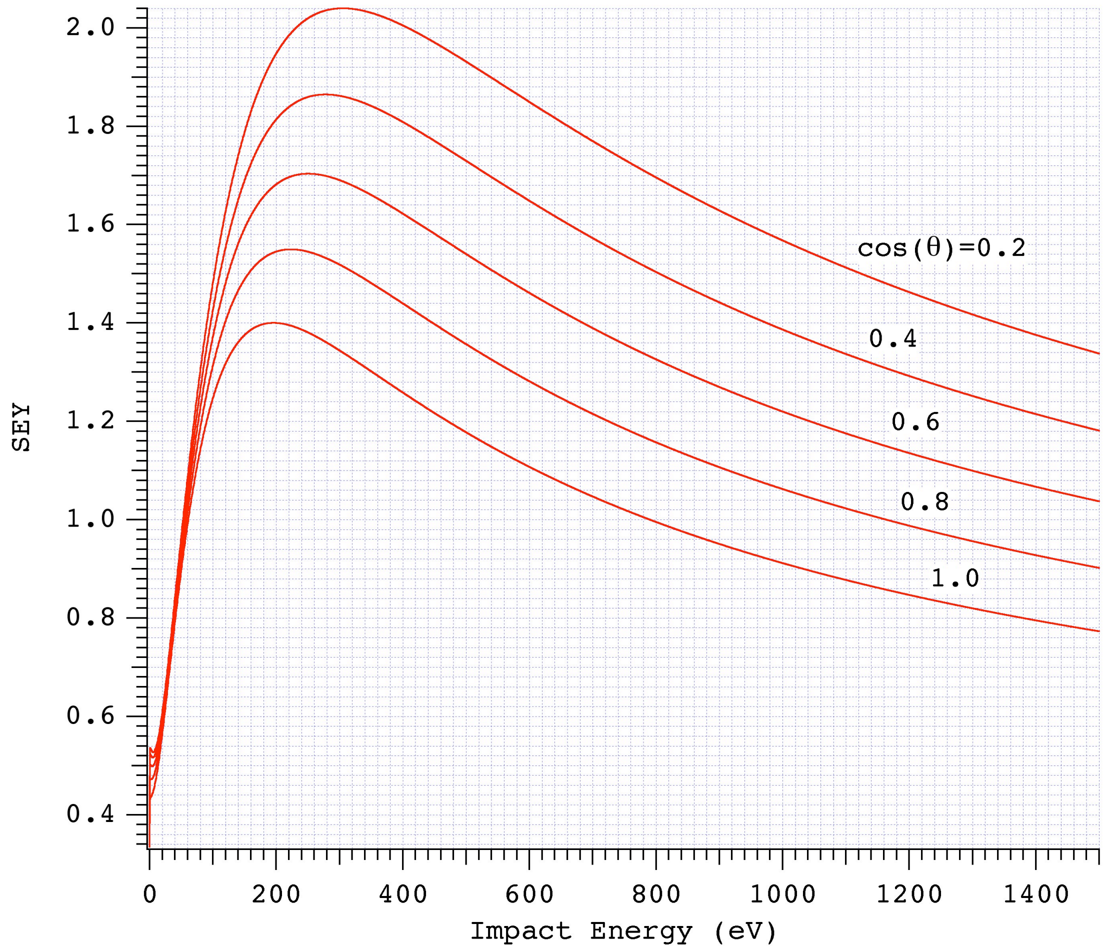
4. Measurements in the PEP-II chicane detected the resonances. CesrTA will continue exploration of their effects.

5. This resonant effect produces an increase in the electron cloud density that is not huge (factor ~2-3), but the effect is periodic in z if B is, and could lead to a resonant effect on the beam.

Similar resonance with ions: G. Rumolo and F. Zimmerman, "Interplay of Ionization and Sputtering with the Electron Cloud", CERN-SL-2001-0140AP.

Extra Slides

Secondary Yield vs. E,θ for our Parameters

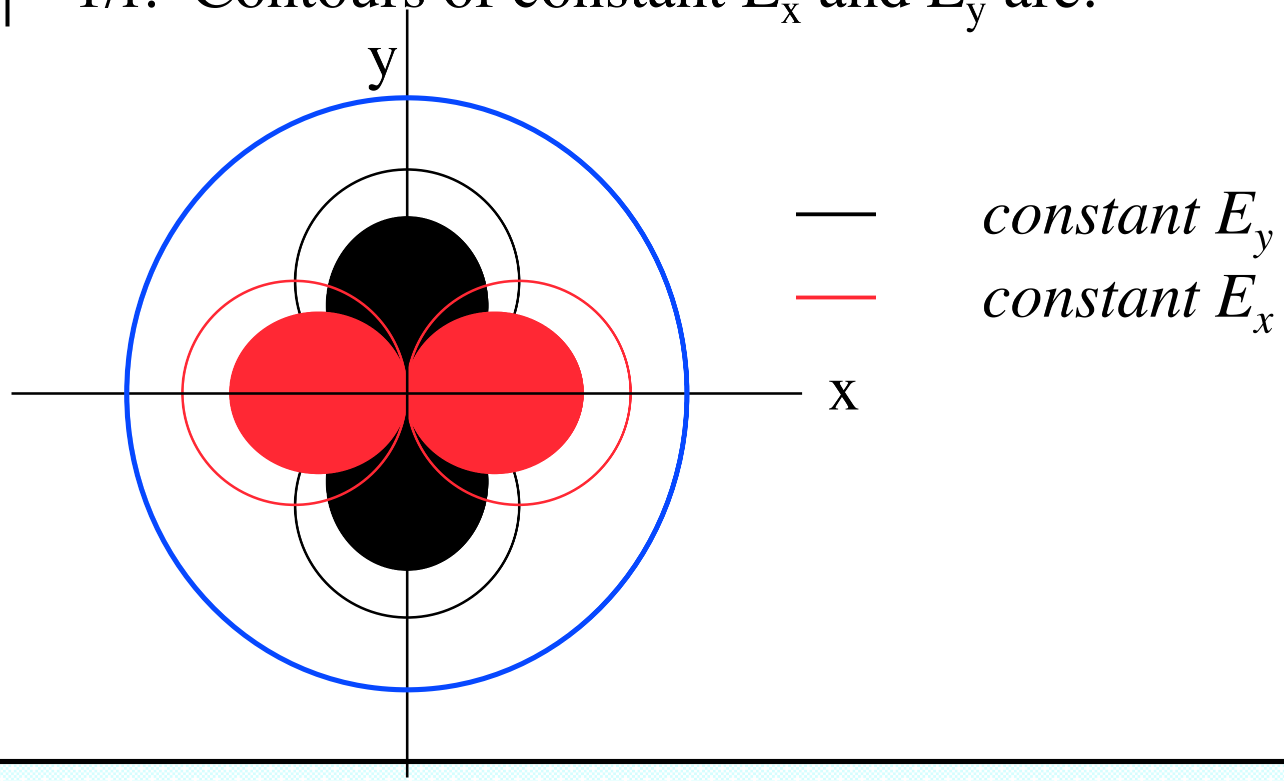


At resonance both the x and y beam kicks are important to increasing the energy

In what part of the chamber is the beam force most effective?

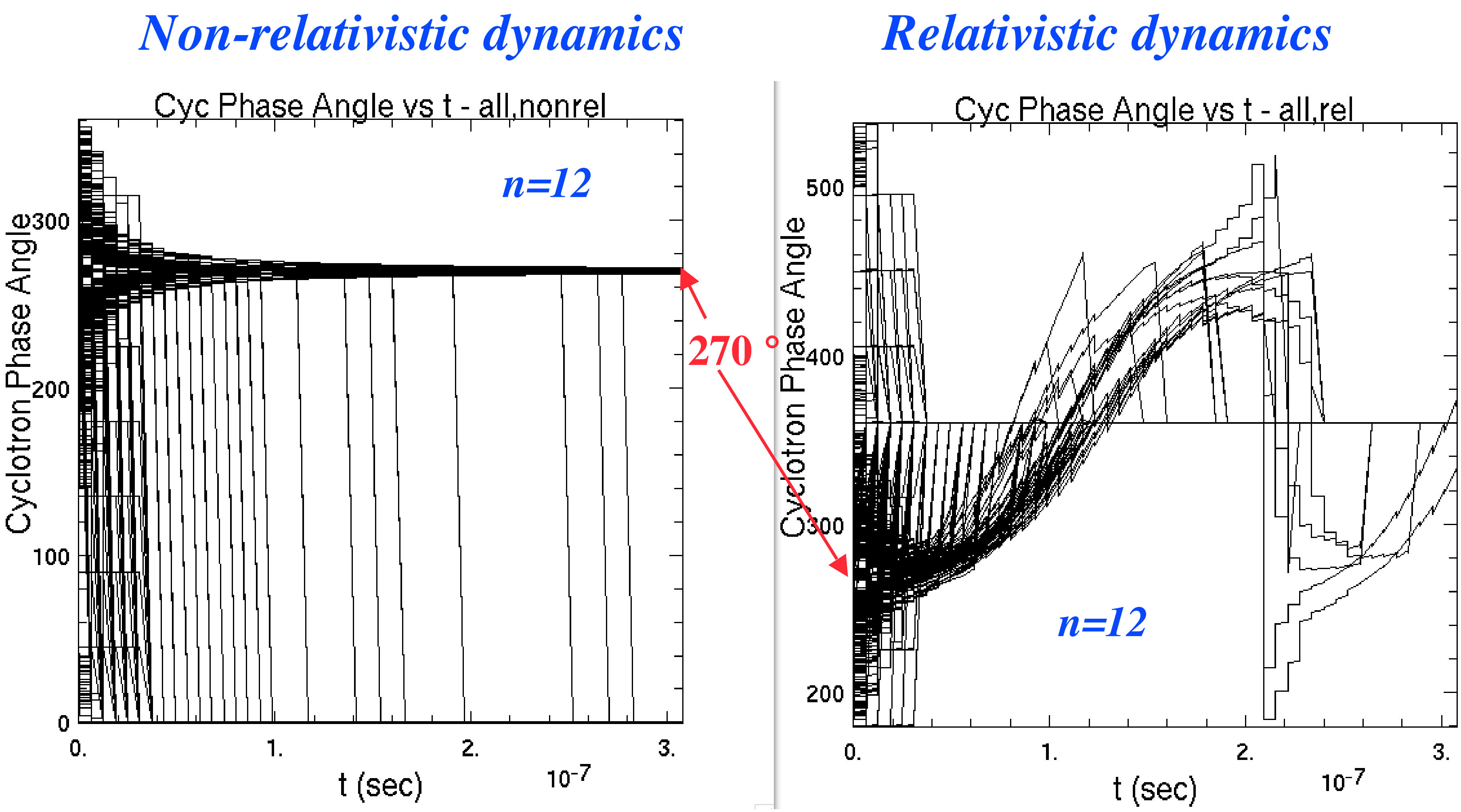
Assume $r >> \sigma_x$, $r >> \sigma_y$.

Then $|E| \propto 1/r$. Contours of constant E_x and E_y are:



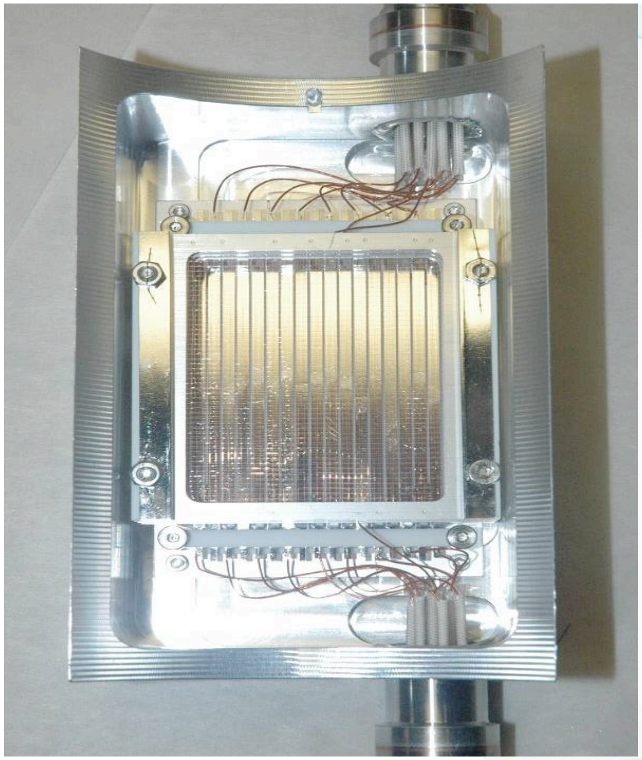
So at resonance, more electrons can pick up the energy needed to make secondaries.

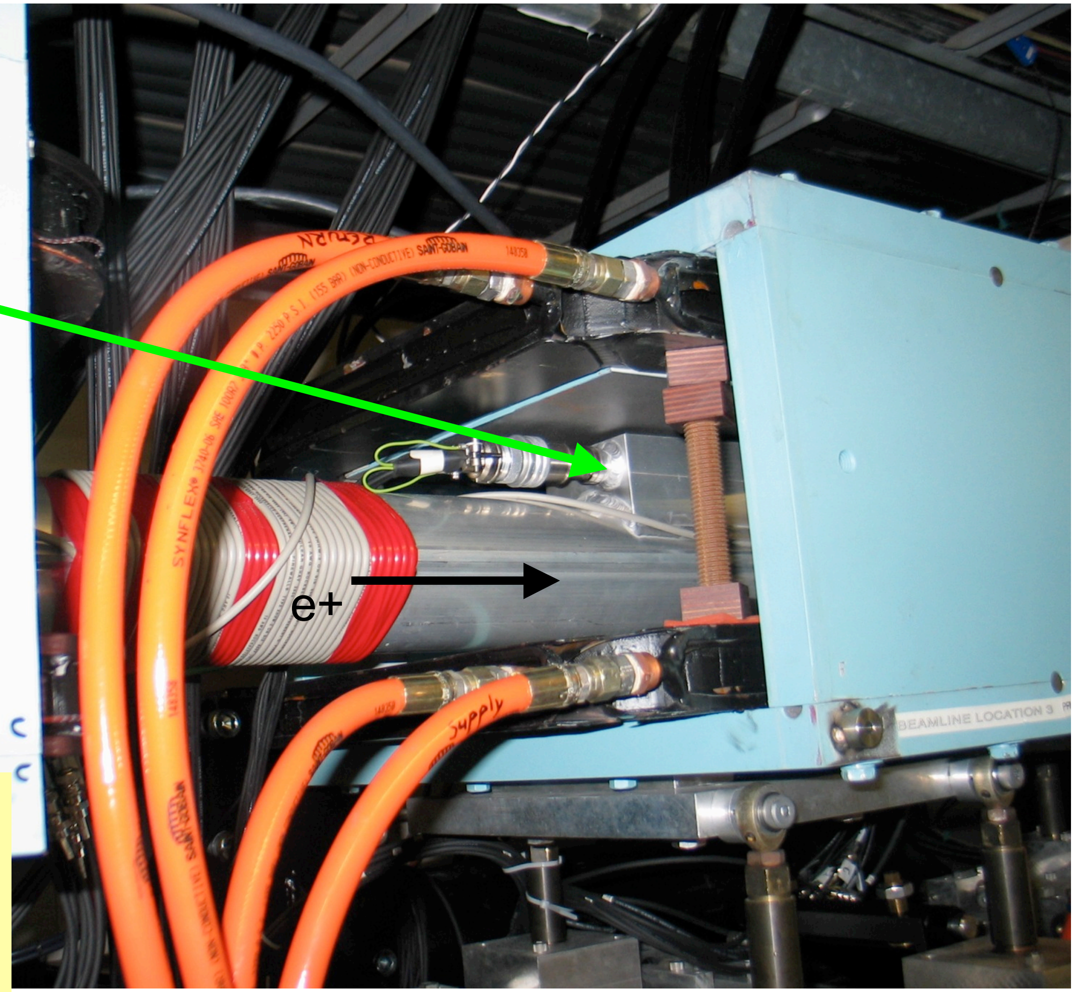
With proper relativistic dynamics, electrons detune



Note: when electrons hit the wall, their angle is set to zero (gives vertical lines)

Instrumentation

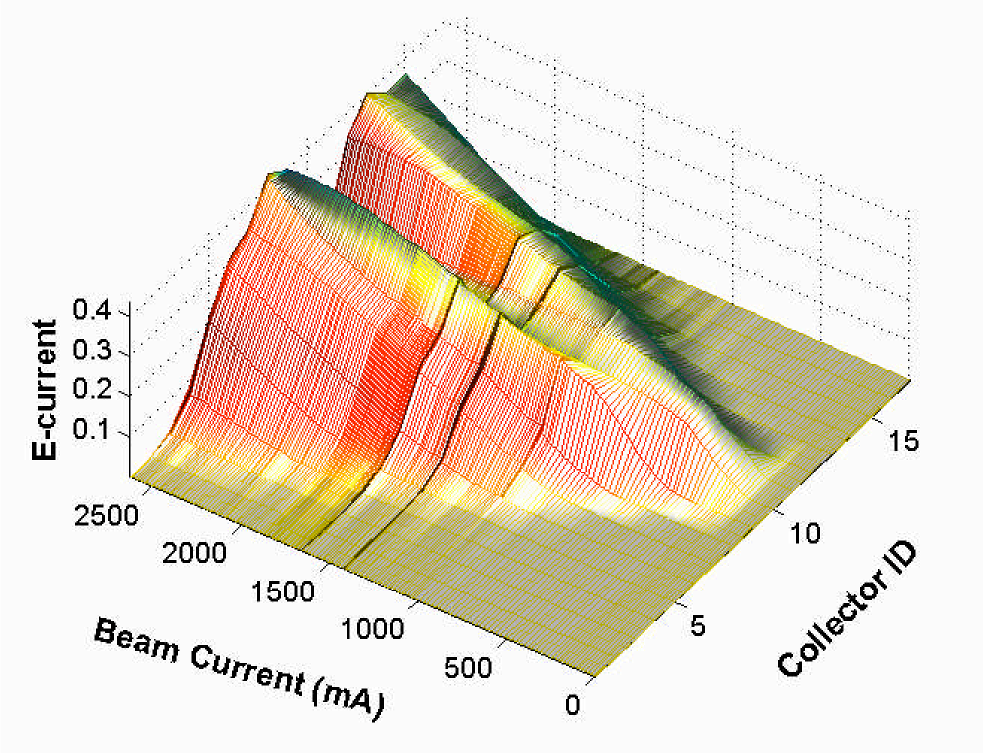




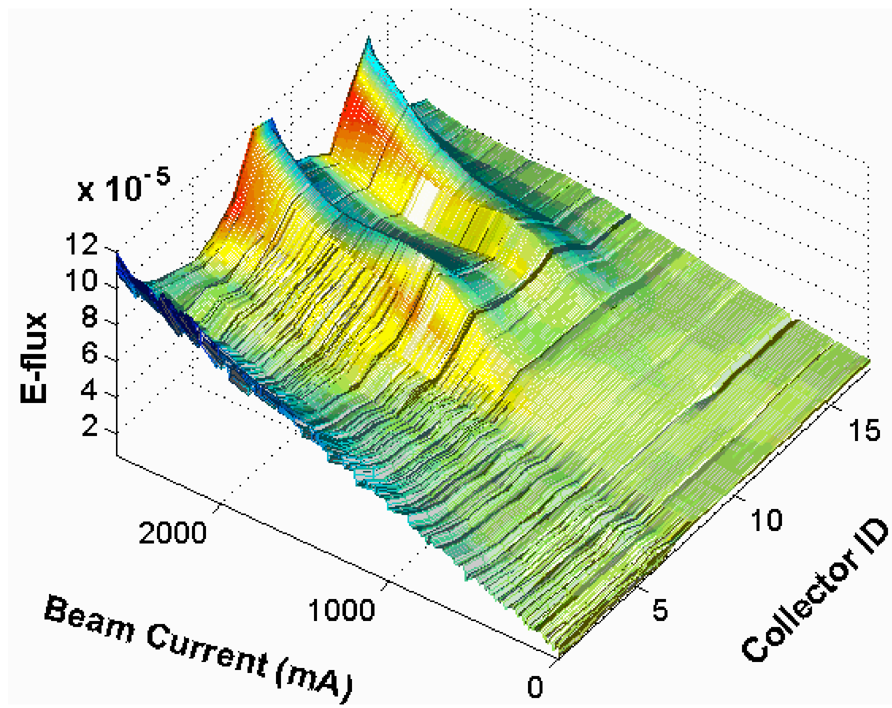
Retarding Field Analyzer (RFA):
- electron flux at the wall
- energy spectrum
- lateral distribution

Beam Current Dependence

Uncoated aluminum chamber



TiN-coated aluminum chamber



Lateral distribution consistent with simulation.

L. Wang et al, SLAC

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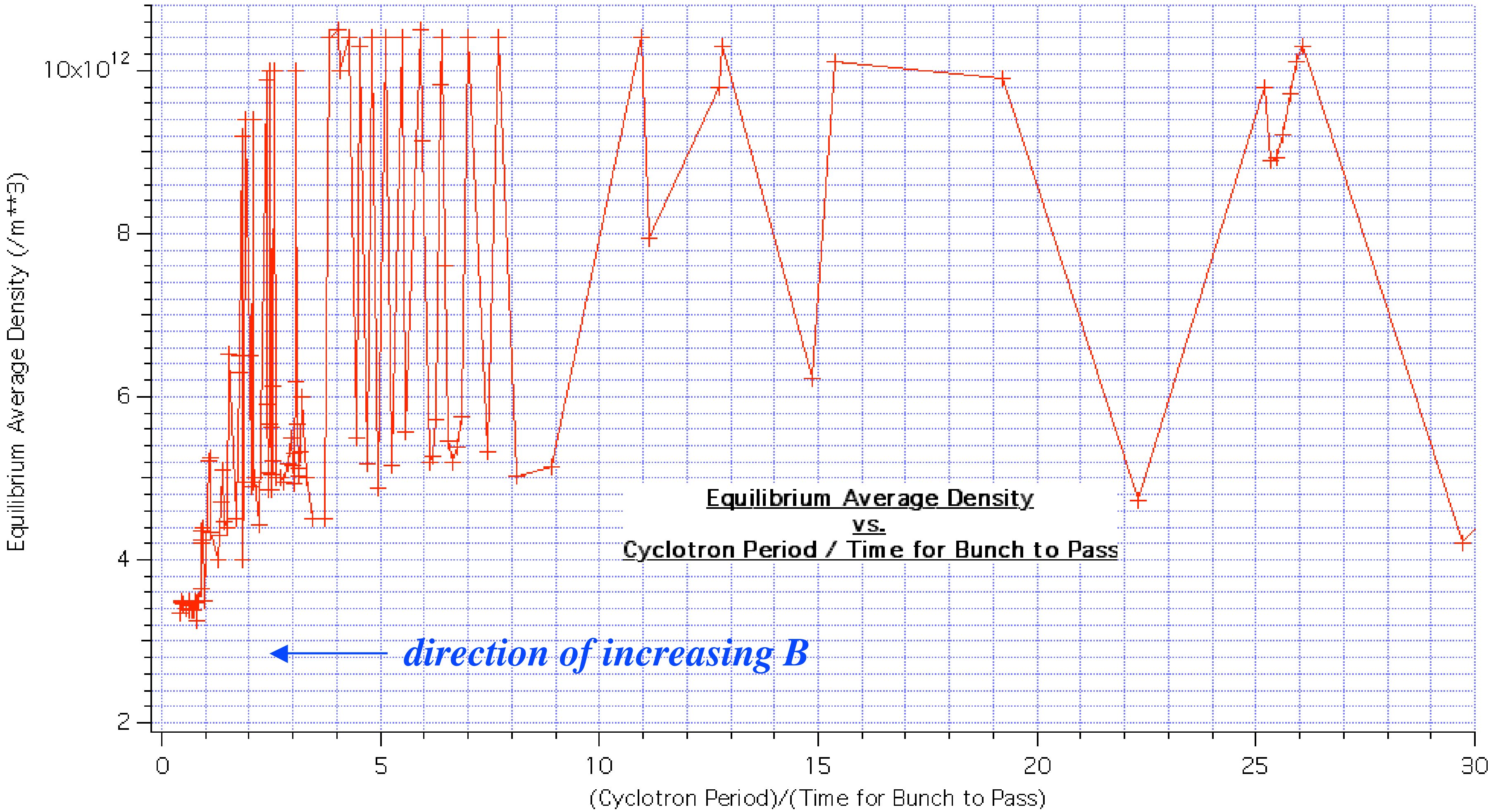
Another View - Peak amplitude falls off as cyclotron period decreases



Note: This is probably the reason this effect has not been seen before-- in other machines the bunch length was much longer, and the B's studied were higher.