Multipacting and remedies of electron cloud in long bunch proton machine

? Analysis, simulation and experiment

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Ref: BNL/SNS TECH NOTE 132 & 128

Acknowledges: J. Wei, M. Blaskiewicz, H.C. Hseuh, P. He, Y.Y Lee, D. Raparia, S.Y. Zhang(BNL), R. Macek (LANL), K. Ohmi (KEK), A. Chao (SLAC)

OUTLINE

- Motivation
- Mechanism of multipacting
- Important factors related to Multipacting
- Multipacting in Dipole, Quadrupole magnets
- E-cloud clearing with solenoids & electrodes
- Summary

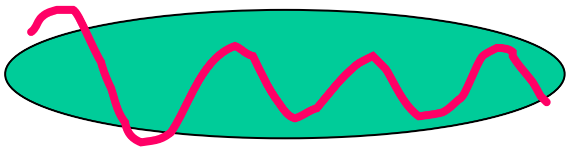
Motivation

- **What is the mechanism of trailing edge multipacting?**
- **Which factors affect e-cloud multipacting? And How?**
- **How to Clear electron cloud?**

Classification of electron multipacting

If an electron can oscillate many times under the beam force during the passage of one bunch, then the bunch is called long bunch

$$\frac{\hat{z}\overline{w}}{pbc} >> 1$$



Long bunch (Single bunch multipacting): PSR, SNS,JPAC, ISIS, ESS…

Short bunch (Multibunch multipacting): B-factories, PF, NLC damping ring, SPS, LHC, RHIC,…..

Source of electrons

Primary electrons

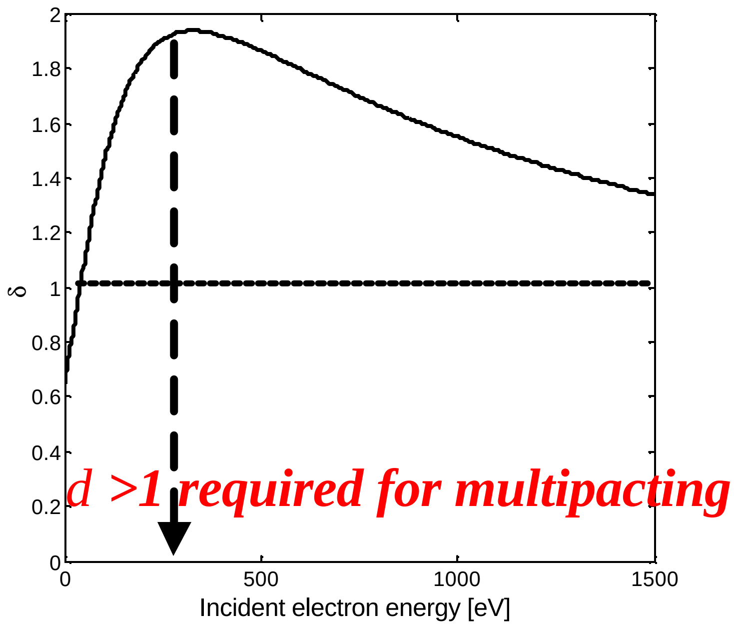
- Photon-electrons (electron machine & LHC)
- **Beam loss** at the chamber surface (PSR, SNS, ISIS, ESS, JPARC)
- Residual gas ionization
- **Stripped electrons**
- …….

Parameters for the SNS Accumulator Ring

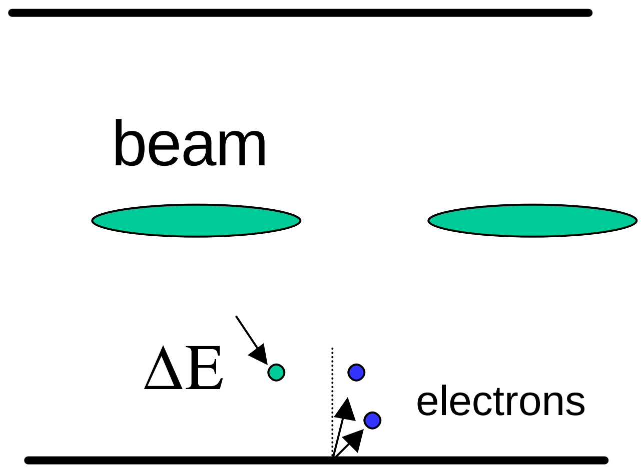
Parameter	Description	SNS
E (GeV)	Beam energy	1.9
C (m)	Circumference	248
N_p	**Beam intensity**	**2.05´10^{14}**
a_x,a_y (mm)	Transverse beam size	28, 28
τ_b (ns)	**Bunch length**	***700***
b (cm)	Beam pipe radius	10
P_l	Proton loss rate/turn	1.1×10^{-6}
Y	Assumed proton-electron yield	100

Secondary electrons

Secondary emission yield



Beam driven multipacting



Key parameters for Multipacting (Strong energy and SEY dependence)

- SEY depend on the material property of the chamber surface (peak SEY and energy at peak SEY)

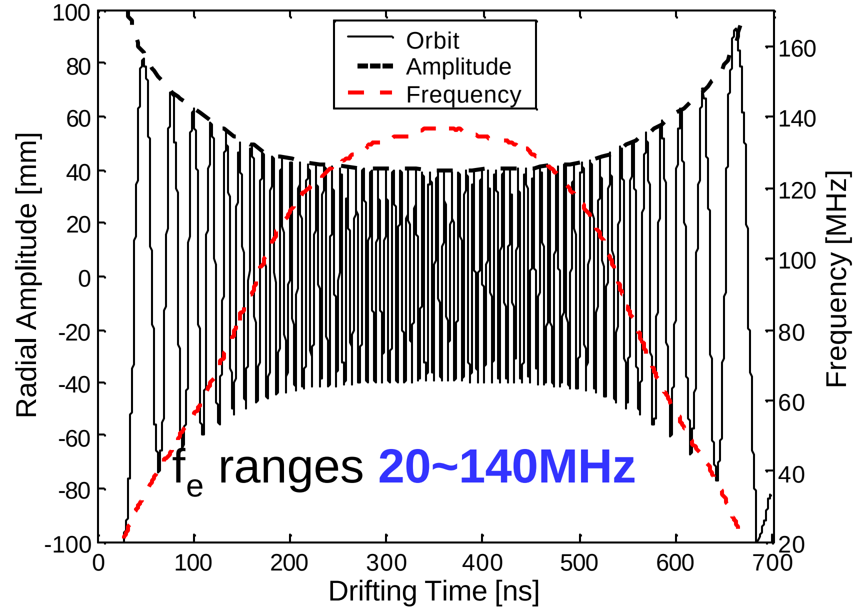
- Beam-electron interaction dependence (beam pattern, bunch current, bunch shape, bunch length, chamber size…)

Nonlinear Oscillation Period and Adiabatic invariant

Nonlinear Oscillation Frequency

$$T = 4.0\int_0^{r_{amp}} \frac{dr}{u(r)} = 4.0\int_0^{r_{amp}} \frac{dr}{\sqrt{2\Phi e/m}}$$

$$T = \begin{cases} 4.0\sqrt{\dfrac{pe_0 m}{le}}\left(\sqrt{2}a \arcsin\dfrac{1}{\sqrt{1+2\ln(r_{amp}/a)}} + \displaystyle\int_a^{r_{amp}} \dfrac{dr}{\sqrt{\ln(r_{amp}/r)}}\right) & \\ 2pa\sqrt{\dfrac{2pe_0 m}{le}} & (\mathrm{r_{amp}} \le a) \end{cases}$$



Oscillation amplitude and frequency

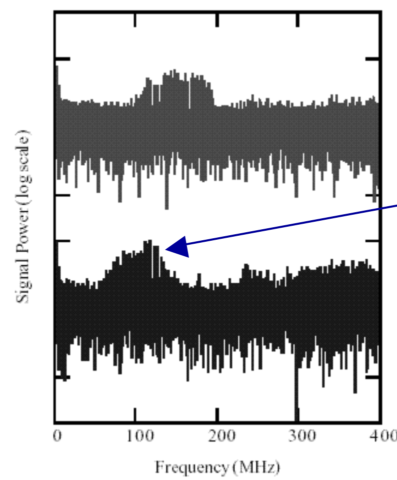
Adiabatic invariant

$$\frac{1}{w_e^2}\frac{dw_e}{dt} << 1 \quad \textit{(if t>20ns and t<680ns for SNS)}$$

$$J = \oint pdq$$

$$J = \begin{cases} \dfrac{pr_{amp}^2}{a}\sqrt{\dfrac{mel}{2pe_0}} & (r_{amp} < a) \\ 4a\sqrt{\dfrac{mel}{2pe_0}}\left(\dfrac{\sqrt{2}}{2}x^{1/2} + \dfrac{1+2x}{2} arctg\dfrac{1}{\sqrt{2x}} + \dfrac{\sqrt{2}}{a}\displaystyle\int_a^{r_{amp}} \sqrt{\ln\dfrac{r_{amp}}{r}}dr\right) & (r_{amp} > a) \end{cases}$$

$$x = ln(r_{amp}/a)$$



LANL PSR

beam spectrum

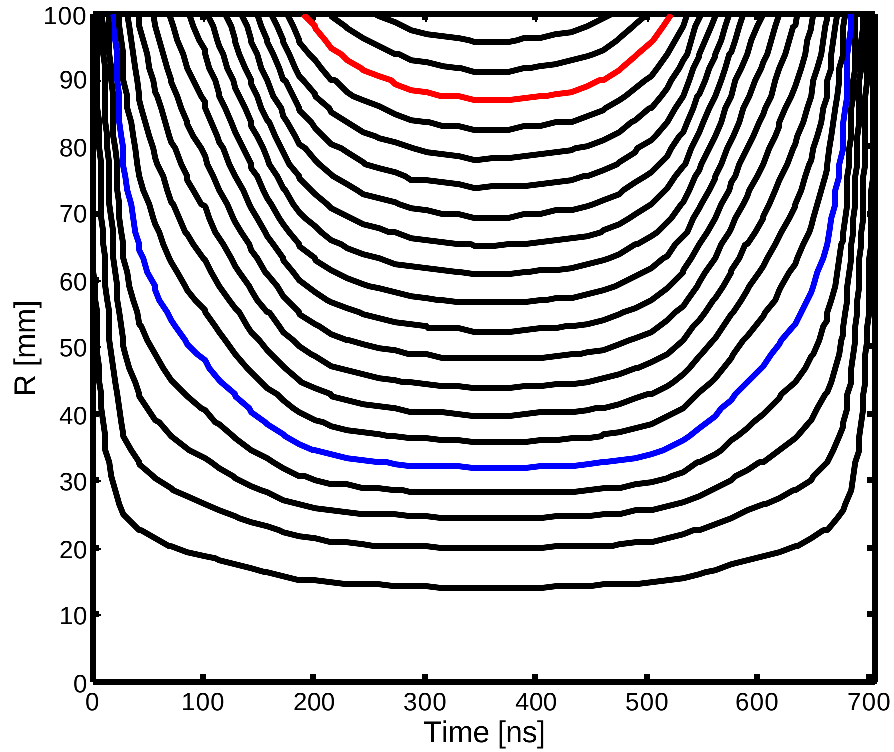
50~150MHz

courtesy

Robert J. Macek

Oscillation amplitude from adiabatic invariant

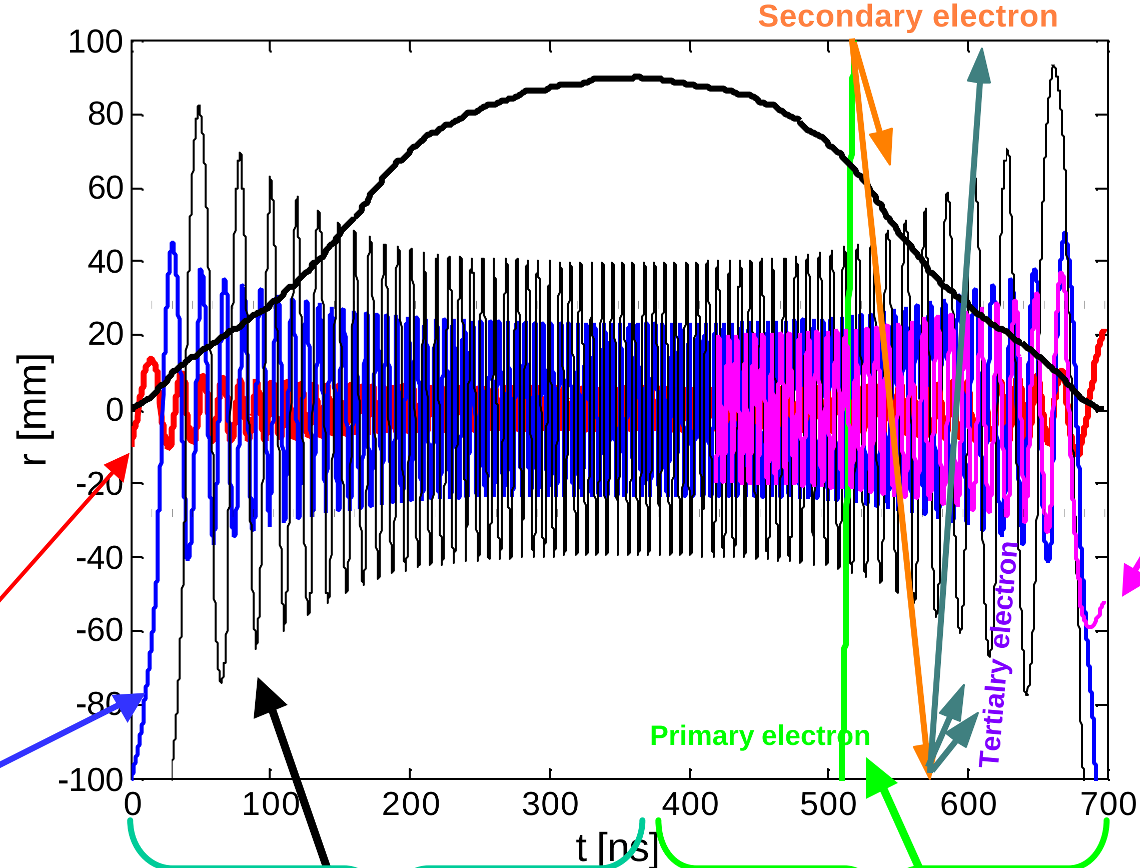
- Contour plot from adiabatic invariant can clearly descript the electron orbit
- All electron emitted (including gas ionization) before the bunch center or survived from last bunch gap can be trapped (inside beam for the survived electrons) during the bunch passage and are released at the bunch tail. The trapped electrons, most of them are the survived electrons from the last bunch gap, contribute to beam dynamics (instabilities)
- All electrons which emitted from the wall after bunch center will directly drift to the opposite of wall surface. The straight drifting electrons contribute to multipacting due to their short drifting time &high energy when they hit the wall surface.

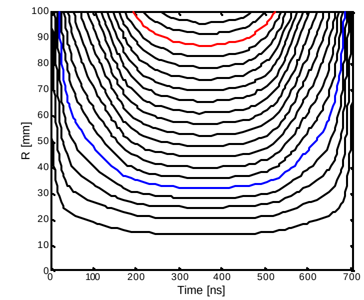


Contour plot of the oscillation amplitude resulting from adiabatic invariant for SNS beam

Particle motion vs. instability & multipacting

Typical orbits of various electrons trapped by SNS beam, bold solid line shows the longitudinal beam profile shape and the dashed back lines show the beam size





Electrons by ionization

(beam instabilities)

Electrons survived from the bunch gap(beam instabilities)

Electrons emitted before bunch center (trapped and lost after bunch center, multipacting)

Electrons emitted after the bunch center(multipacting)

Energy Gain of multipacting electron &
Mechanism of trailing edge multipacting (SNS/BNL Note 132)

Electron energy when a multipacting electron hit the wall

$$\Delta E = -\frac{1}{2}\sqrt{\frac{me}{2pe_0}}bc\left(a(2z-1)\arcsin\frac{1}{\sqrt{z}}+a\sqrt{2\ln\frac{b}{a}}+\sqrt{2}z\int_a^b\frac{dr}{\sqrt{\ln(b/r)}}-\frac{1}{\sqrt{2}}\int_a^b\frac{1+2\ln(r/a)}{\sqrt{\ln(b/r)}}dr\right)\frac{\partial l}{\partial z}\frac{1}{\sqrt{l}}$$

$$\Delta t = 2.0\sqrt{\frac{pe_0 m}{le}}\left(\sqrt{2}a\arcsin\frac{1}{\sqrt{1+2\ln(b/a)}}+\int_a^b\frac{dr}{\sqrt{\ln(b/r)}}\right)$$

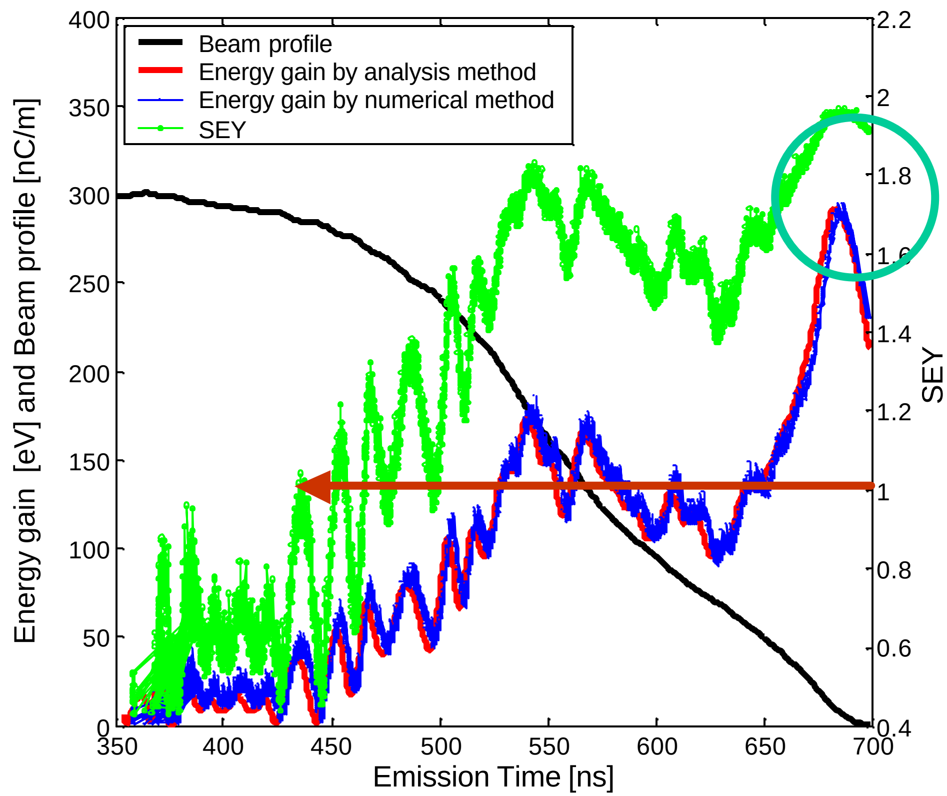
Also see other expressions by M. Blaskiewicz, J. Wei et. al

a: beam size, *b*, chamber radius, λ is beam line density $z = 1+2\ln(b/a)$

Longitudinal beam profile factor

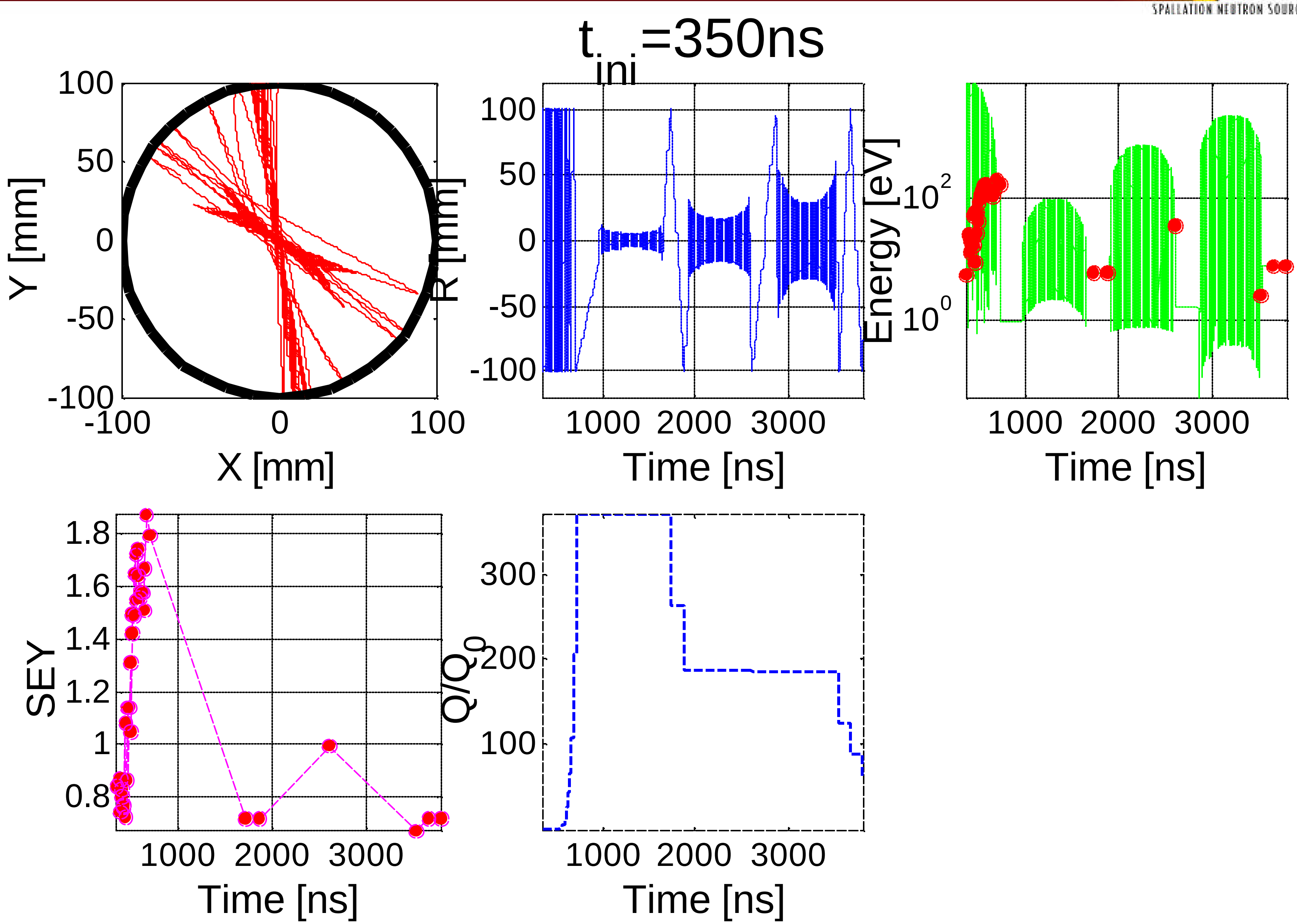
$$Factor_{profile} = -\frac{\partial ?}{\partial z}\frac{1}{\sqrt{?}}$$

- Good agreement with numerical method
- Calculated SEY can be used to predict the multipacting directly
- Adiabatic motion and Energy gain can explain the mechanism of "trailing edge multipactor"



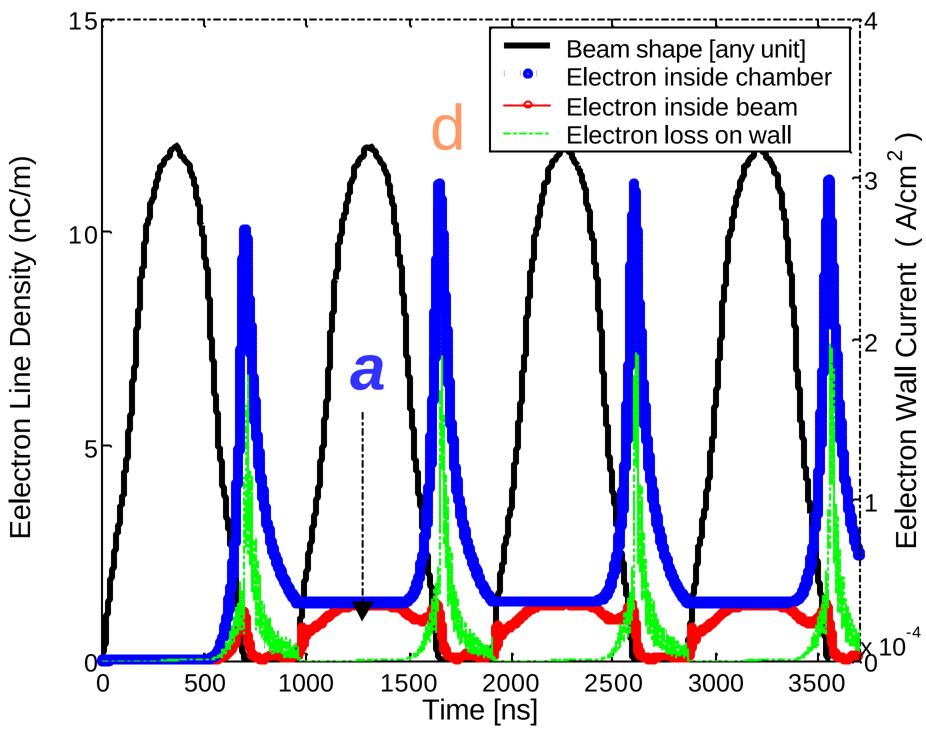
L. Wang 4/20/2004

Sample I: Multipacting → trapped electron

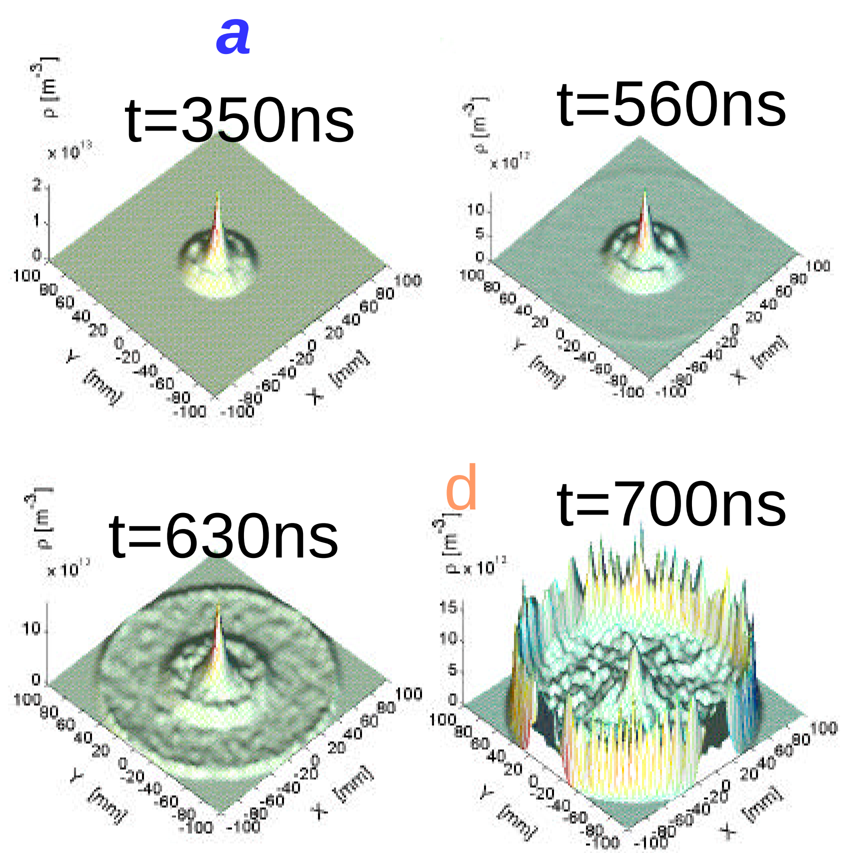


E-cloud in drift region

- **Single bunch multipacting & Trailing Edge Multipacting**
- **All surviving electron from the last gap are trapped inside beam during the bunch passage (Contributing to beam instabilities)**
- **Bunch gap is important for *beam dynamics***

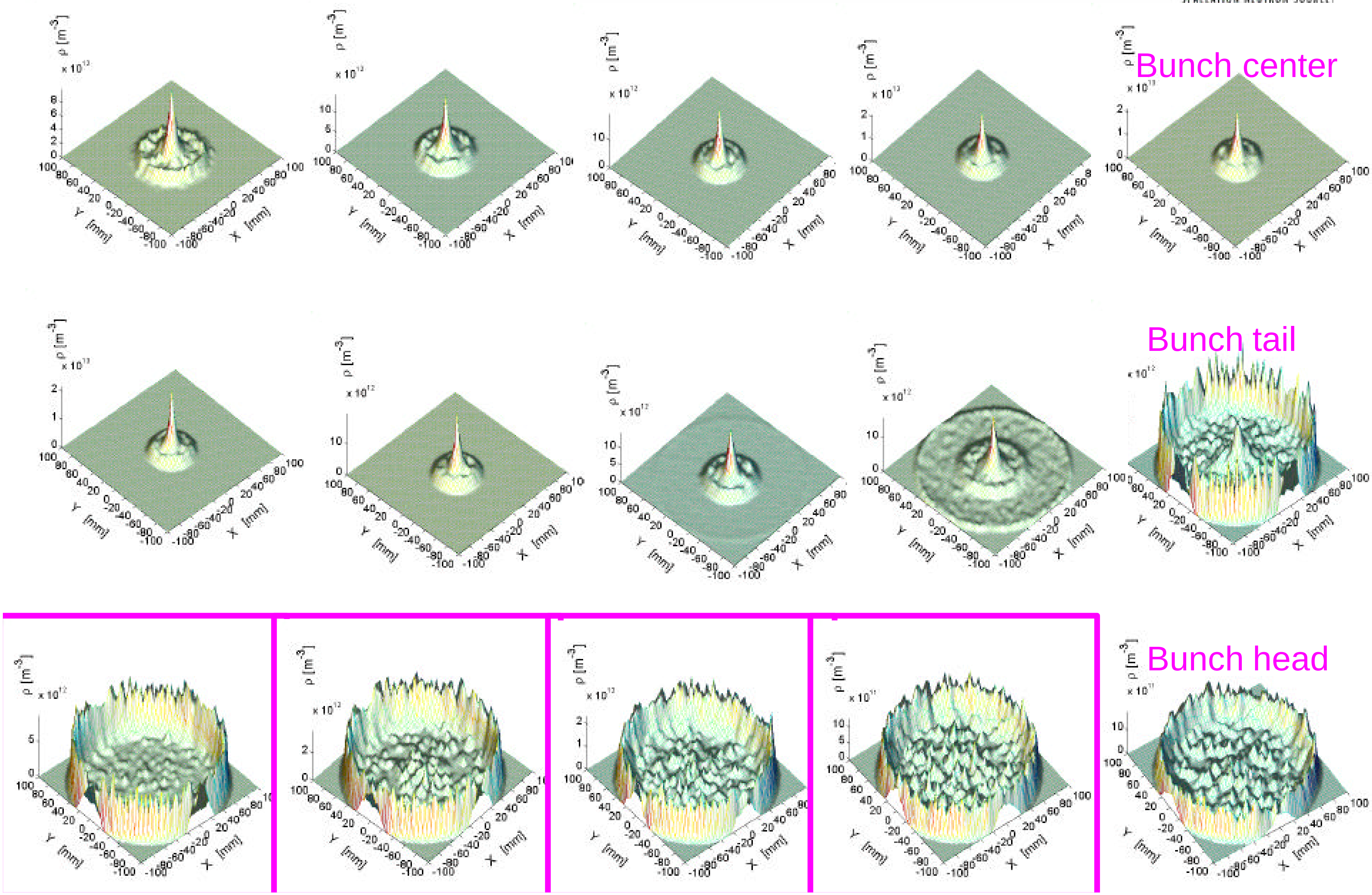


E-cloud build-up in SNS drift region

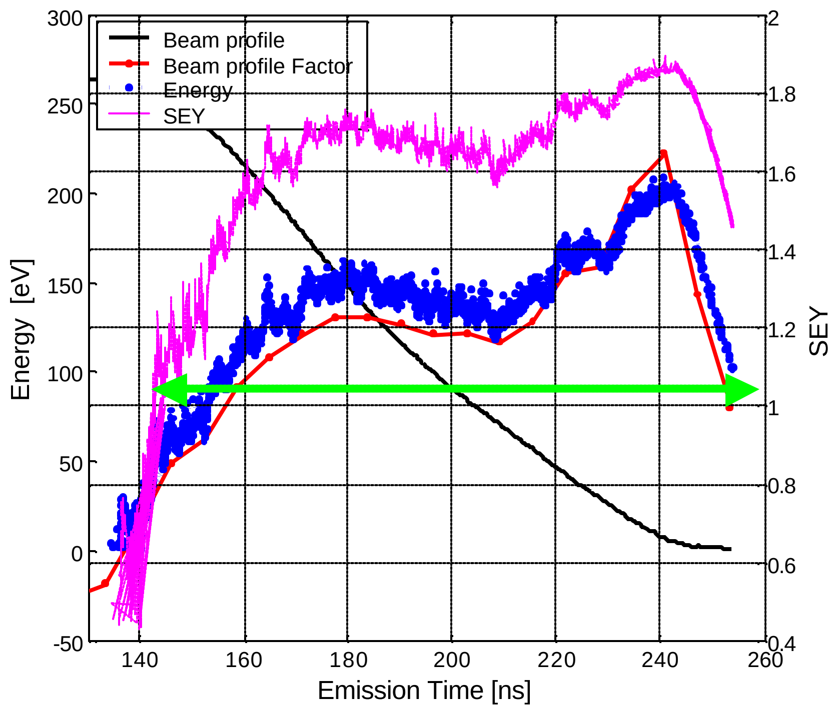


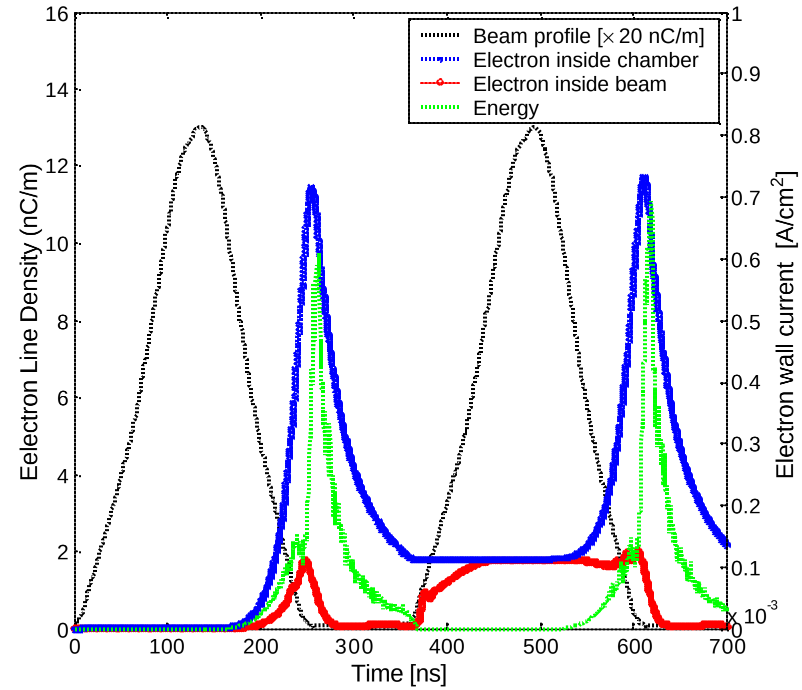
E-cloud distribution in different time

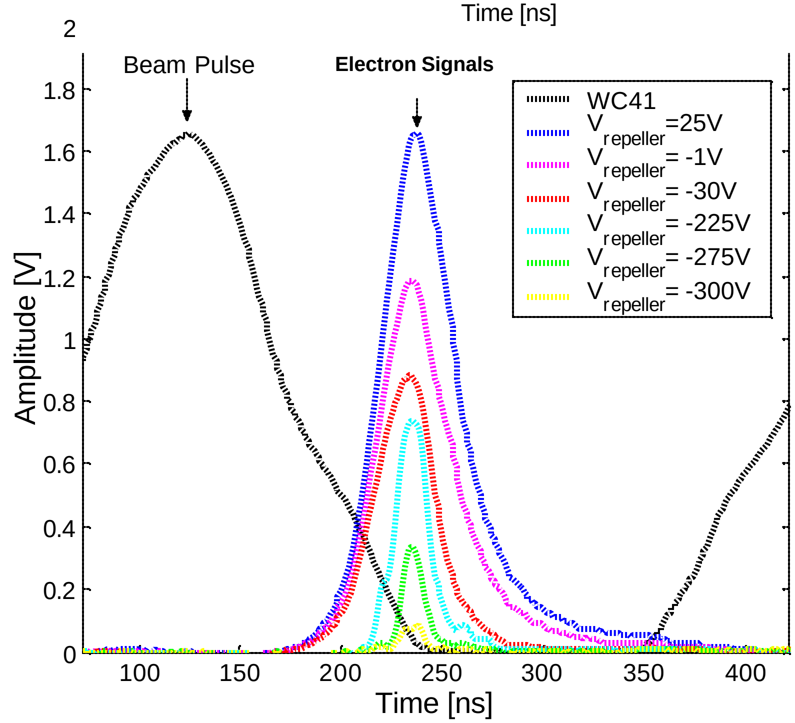
Snapshot for one turn



Ecloud in PSR







Comparison with experiment:
Electron energy at the wall 0~200eV
(experiment 0~300eV)
Wall current 0.7mA/cm^2
(experiment 0.4mA/cm^2)

ED42Y Signals for various repeller voltages

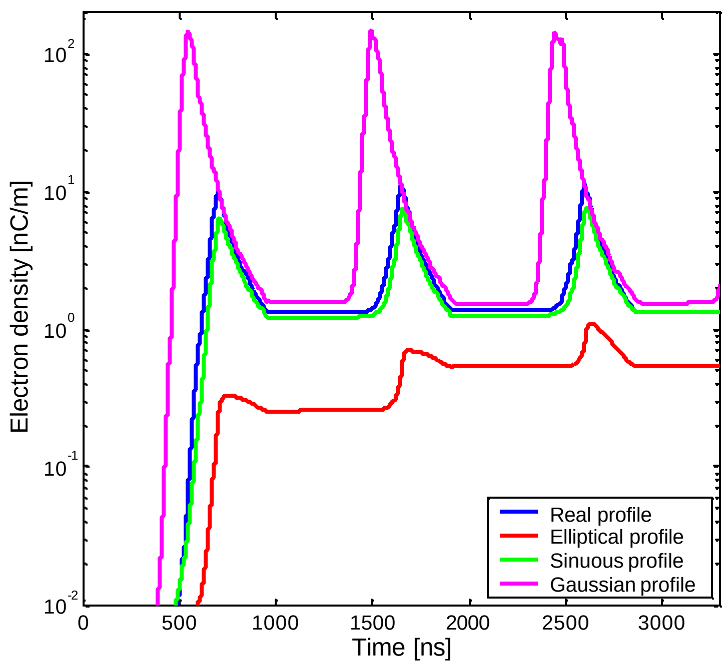
courtesy **Robert J. Macek**

Important parameters related to multipacting

Parameters	Effects		mechanism
	$\rho_{chamber}$ (Multipacting)	ρ_{beam} (stabilities)	
Longitudinal beam profile	**sensitive**	**sensitive**	**profile factor**
Beam intensity	**very sensitive (no saturation)**	**very sensitive (saturates)**	**multipacting frequency & energy gain**
Beam transverse profile	**insensitive**	**insensitive**	**space charge doesn't sensitive to transverse profile**
Flat beam	**effective**	**effective**	**Electron orbit polarization**
Peak SEY	**Effective (~linearly)**	**Effective (~saturates)**	**SEY**
Energy at peak SEY	**Effective (~linearly)**	**Effective (~linearly)**	**energy gain close to energy at peak SEY**
Electrons by ionization	**insensitive**	**insensitive**	**adiabatic motion (trapping)**
Bunch gap	**insensitive**	**effective**	**single bunch multipacting /decay & trapping**

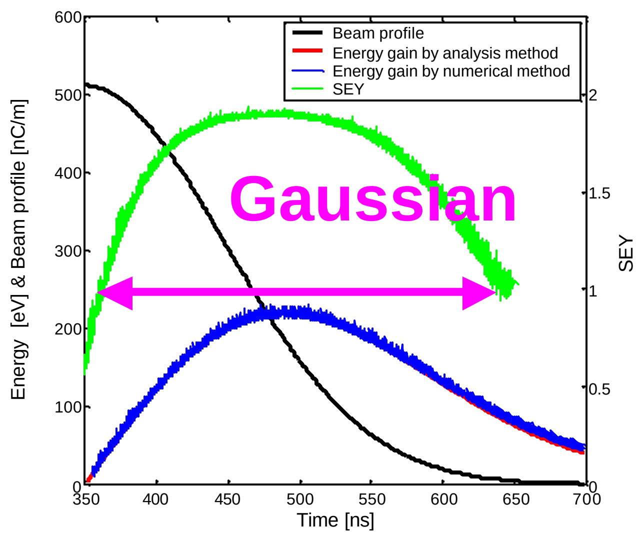
Important Factors Related to Electron multipacting(1)

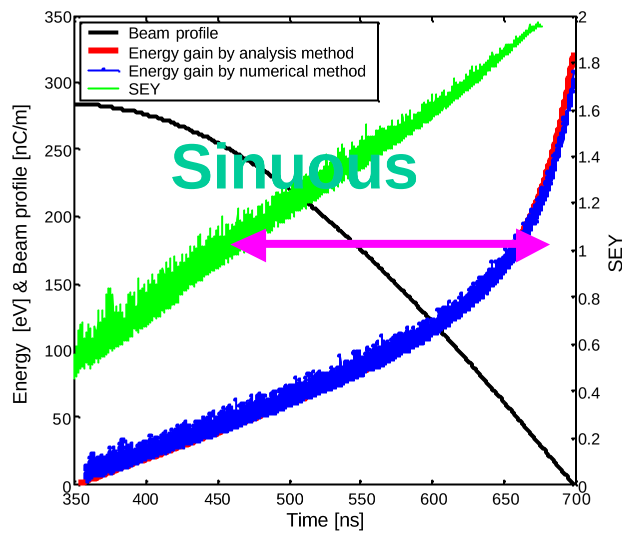
Longitudinal Beam Profile

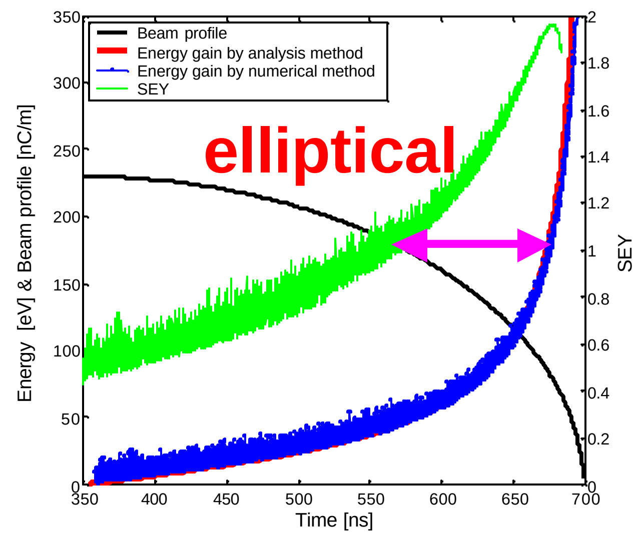


For assumed Gaussian, sinuous & elliptical beam profile:

- **Gaussian profile excites the strongest multipacting due to long bunch tail**
- **Elliptical profile has the weakest multipacting**
- **Electron cloud of the real profile is close to that of the sinuous profile**
- **There is no multipacting for coasting beam**



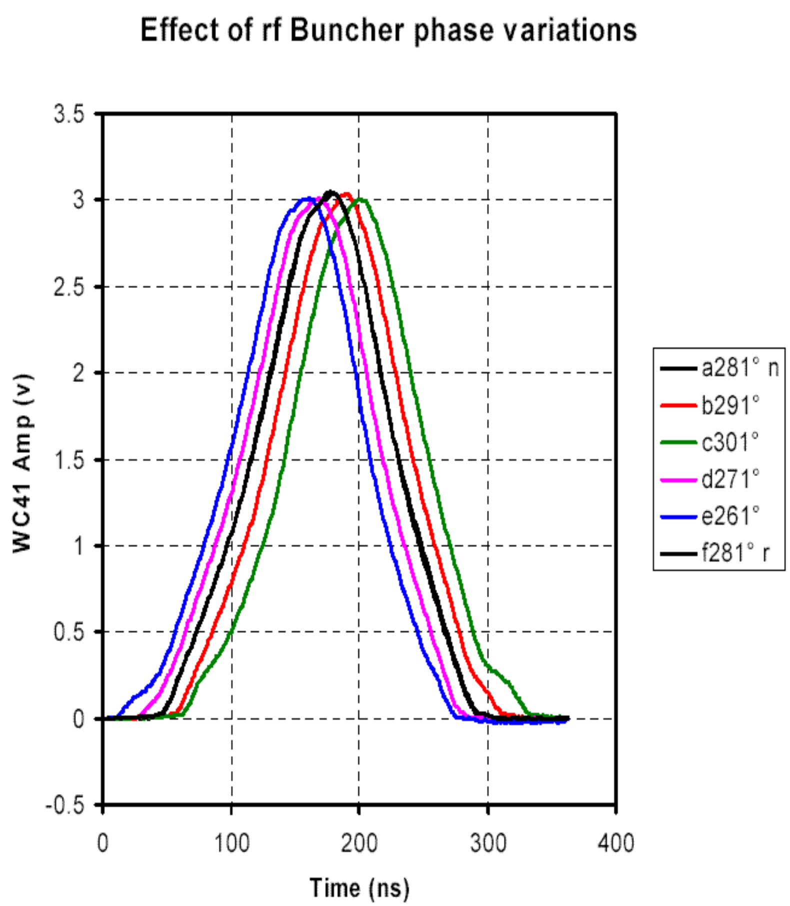




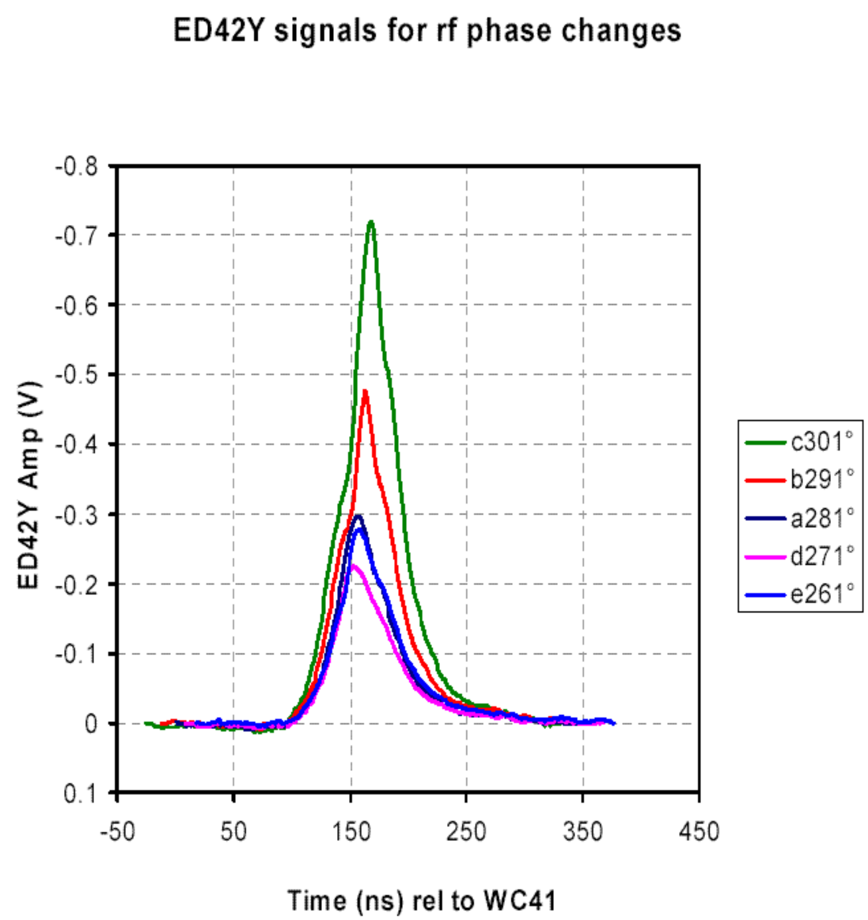
Longitudinal beam profile effects

Electron signals vs bunch shape

(LANL PSR experiment, courtesy **Robert J. Macek, ecloud'02)**



Beam profile with different RF phase

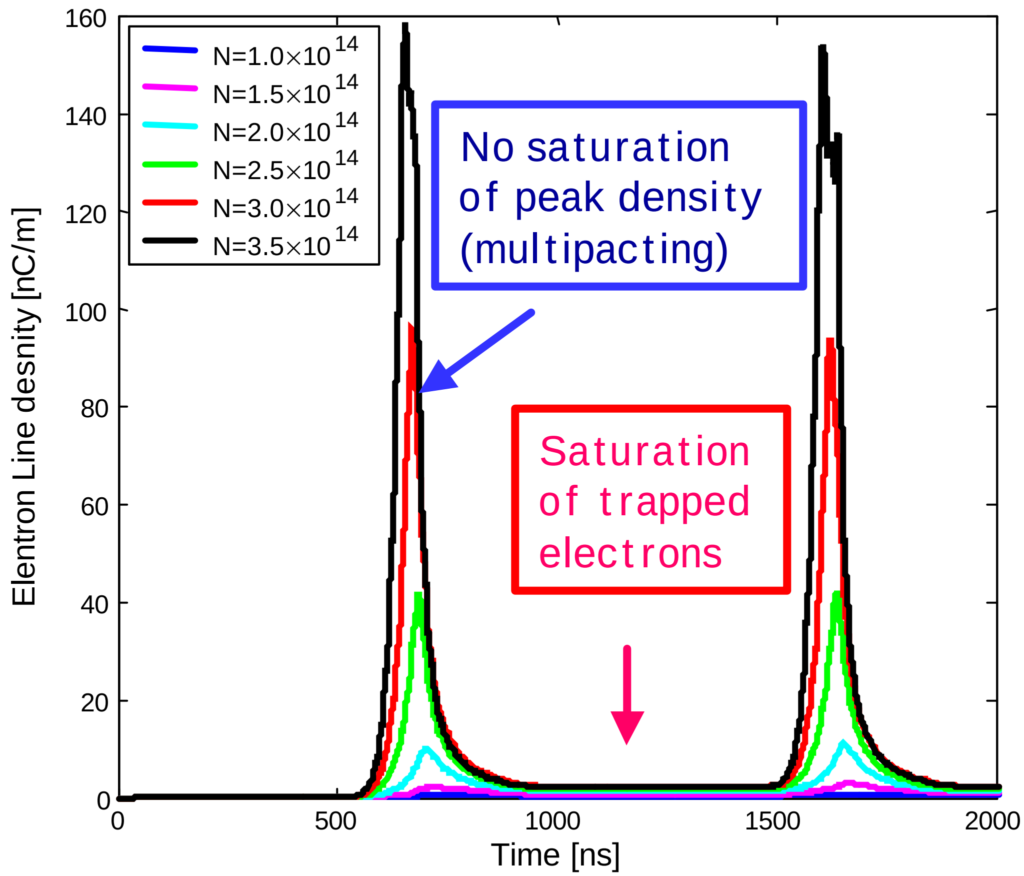


Electron signal with different RF phase

Beam intensity effects (I)

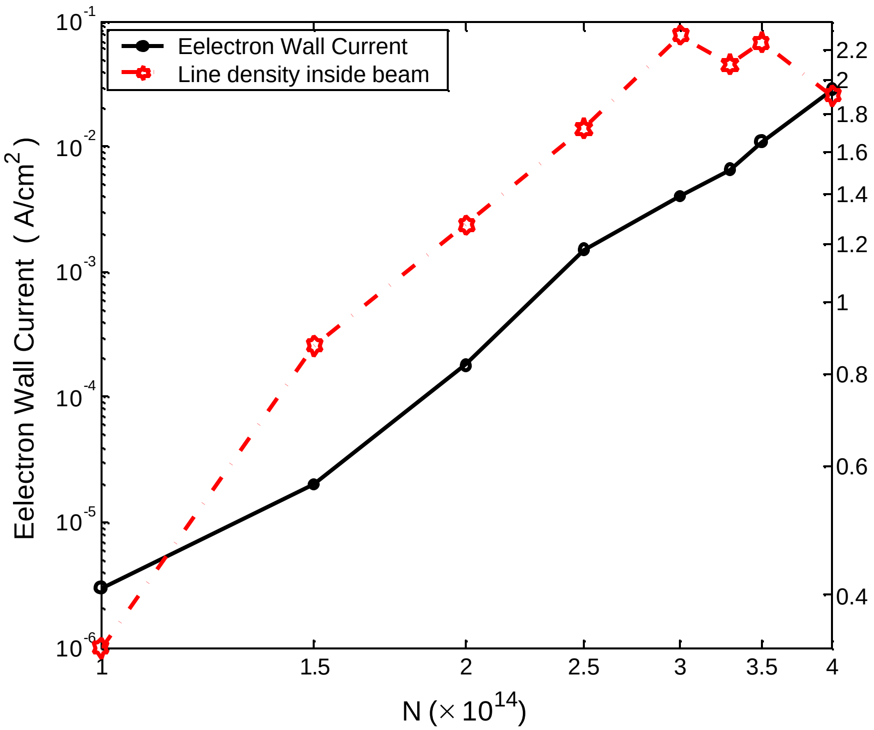
- **High beam intensity causes high electron energy gain** $\Delta E \propto \sqrt{I}$
- **High beam intensity increases multipacting frequency** $f_{multipacting} \propto \sqrt{I}$
- **Space charge slows the growth of electron density inside chamber when strong multipacting case happens**

$$l_{chamber}[nC/m] = 78 - 112\times 1.0^{-14} N + 39\times 1.0^{-28} N^2$$

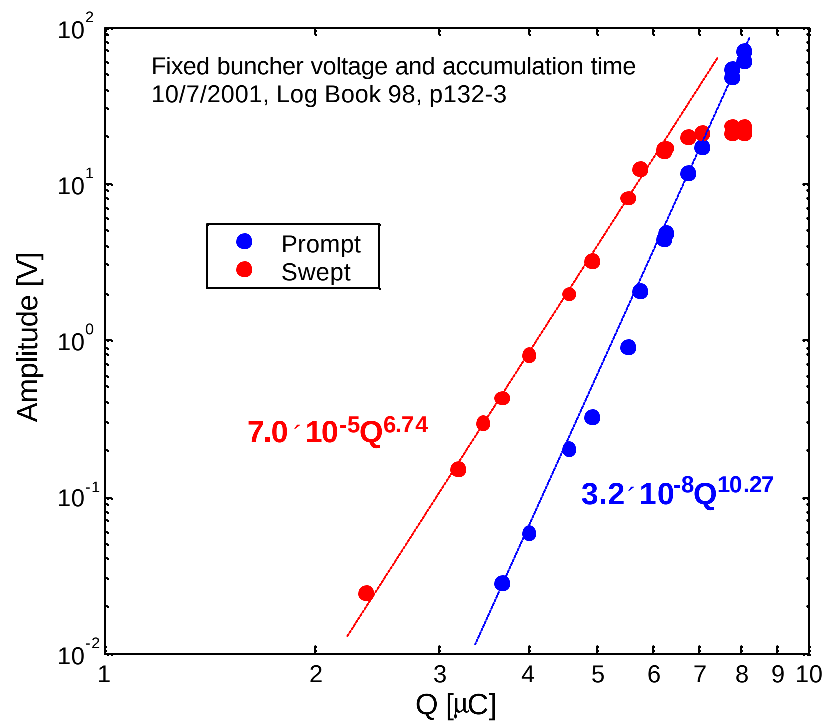


Beam intensity effects (II)

- **Space charge makes the electron density inside beam saturated when strong multipacting case happens**



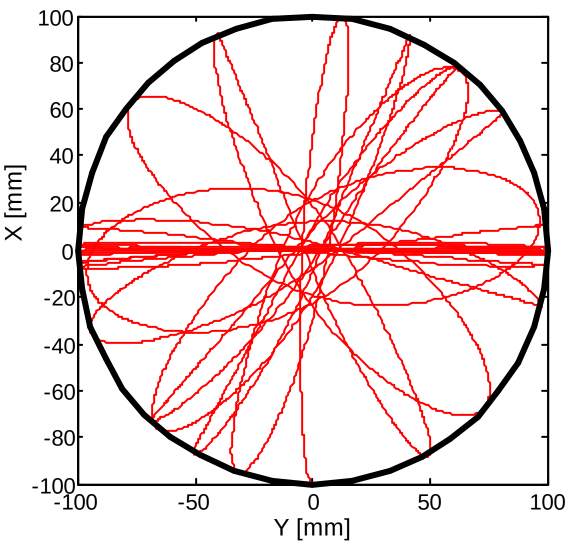
SNS, simulation

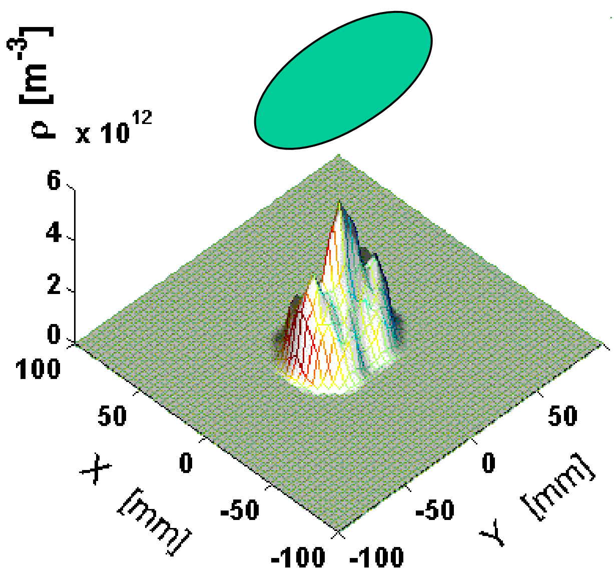


LANL PSR, Experiment, R. Macek

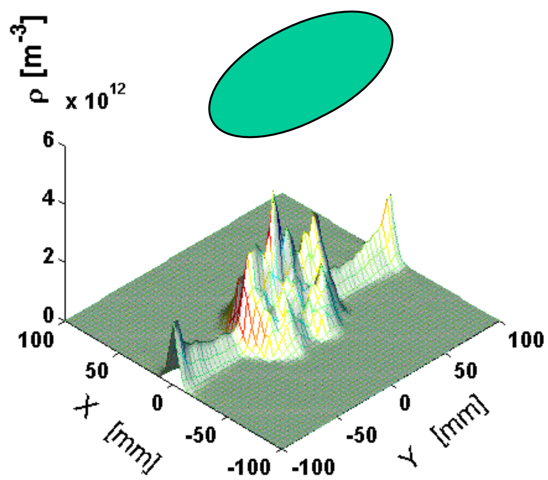
Flat beam effect on EC distribution

- **Flat beam $\sigma_y : \sigma_x = 2:1$**
- **Stronger multipacting in larger beam size direction due to the "polarization effect" of beam space charge force**

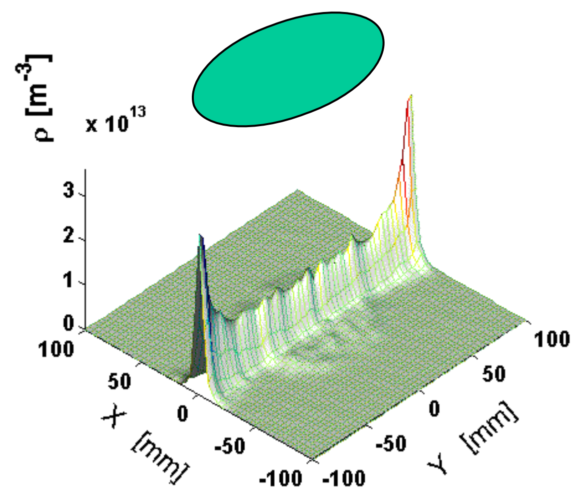




t=350ns



t=560ns



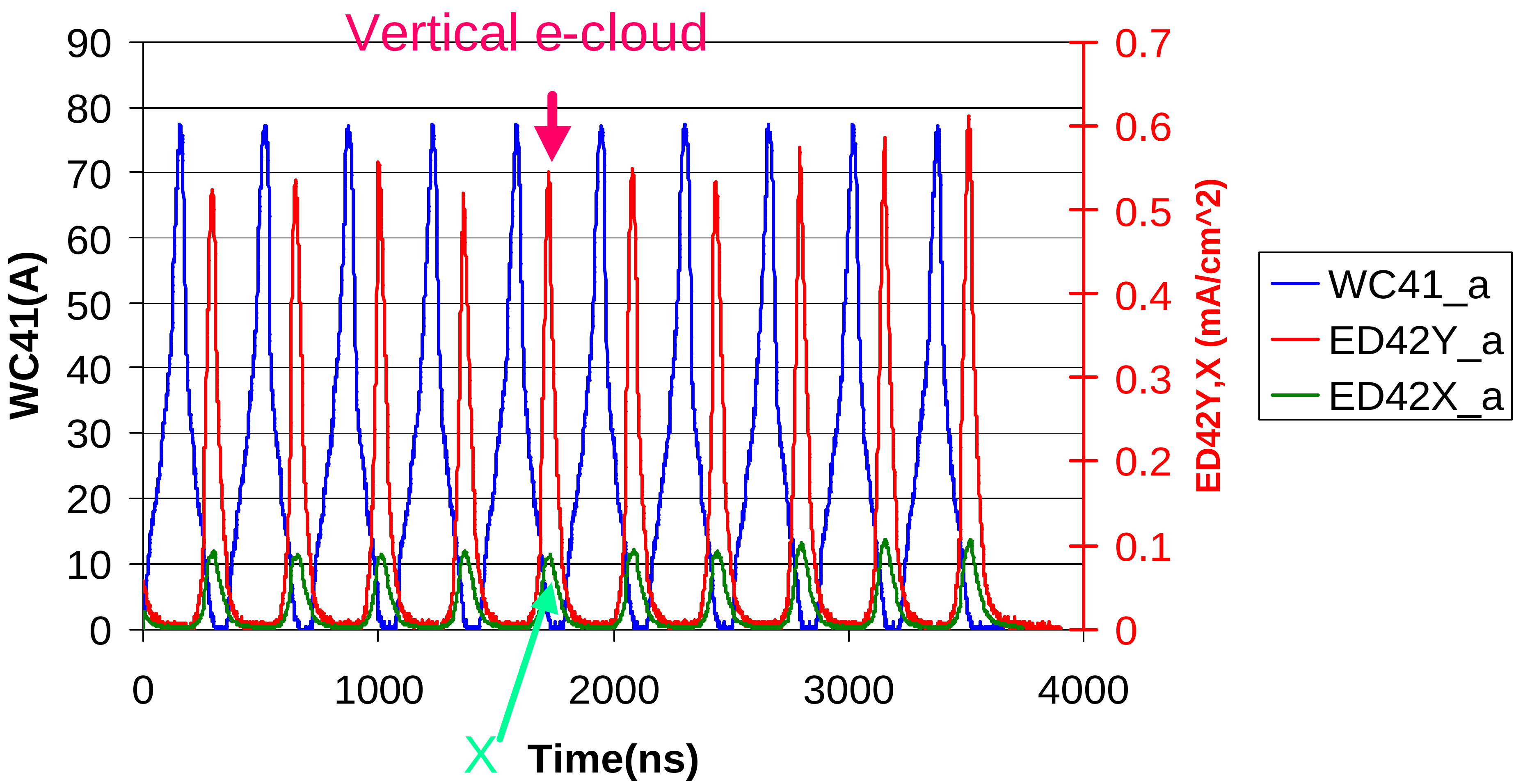
t=630ns

Influence of transverse beam profile

(LANL PSR, Experiment, R. Macek)

spot size estimates: σ_y = 11 mm, σ_x = 5 mm

No Notch beam 11/18/99, 8.83 μC/pulse



Electron motion in dipole magnets

- **Dipole magnetic field B**=(0,By,0)

$$\frac{du_y}{dt} = eE_y / m$$

$$u_x = u_{x0}\cos wt + u_{z0}\sin wt + \frac{E_{x0}}{B}\sin wt + \frac{1}{wB}\frac{dE_x}{dt} - \frac{1}{wB}\left(\frac{dE_x}{dt}\right)_0 \cos wt$$

$$-\frac{1}{wB}\cos wt\int_0^t \frac{d^2E_x}{dt^2}\cos wt dt - \frac{1}{wB}\sin wt\int_0^t \frac{d^2E_x}{dt^2}\sin wt dt$$

$$u_z = u_{z0}\cos wt - u_{x0}\sin wt + \frac{E_{x0}}{B}\cos wt - \frac{E_x}{B} - \frac{1}{B}\cos wt\int_0^t \frac{dE_x}{dt}\cos wt dt + \frac{1}{B}\sin wt\int_0^t \frac{dE_x}{dt}\sin wt dt$$

- In strong dipole magnet(B~1T for SNS) $\left|\frac{1}{wE_x}\frac{dE_x}{dt}\right| << 1$
- Electron motion ≅ **gyration motion** **+** **translation** (cross-field drifting) + movement along B-field lines
- The kinetic energy of gyration motion and cross-field drifting is **smaller** comparing with the kinetic energy in B-field direction.

Electron energy gain in strong dipole magnet

$$\Delta E(X) = -cb\sqrt{\frac{me}{2pe_0}\frac{\partial l}{\partial z}\frac{1}{\sqrt{l}}}\left(1-\frac{\mathrm{X}^2}{\mathrm{a}^2}+\ln\frac{\mathrm{b}^2}{\mathrm{a}^2}\right)\left(aG+\int_{\sqrt{a^2-X^2}}^{\sqrt{b^2-X^2}}\left(\ln\frac{b^2}{X^2+y^2}\right)^{-1/2}dy\right)$$

$$+\frac{1}{2}cb\sqrt{\frac{me}{2pe_0}\frac{\partial l}{\partial z}\frac{1}{\sqrt{l}}}\int_0^{\sqrt{a^2-X^2}}\frac{y^2}{a^2}\left[\ln\left(1-\frac{\mathrm{X}^2}{\mathrm{a}^2}+\ln\frac{\mathrm{b}^2}{\mathrm{a}^2}+\frac{y^2}{a^2}\right)\right]^{-1/2}dy$$

$$+\frac{1}{2}cb\sqrt{\frac{me}{2pe_0}\frac{\partial l}{\partial z}\frac{1}{\sqrt{l}}}\int_{\sqrt{a^2-X^2}}^{\sqrt{b^2-X^2}}\left(1-\frac{\mathrm{X}^2}{\mathrm{a}^2}+\ln\frac{X^2+y^2}{a^2}\right)\left[\ln\left(\frac{b^2}{X^2+y^2}\right)\right]^{-1/2}dy$$

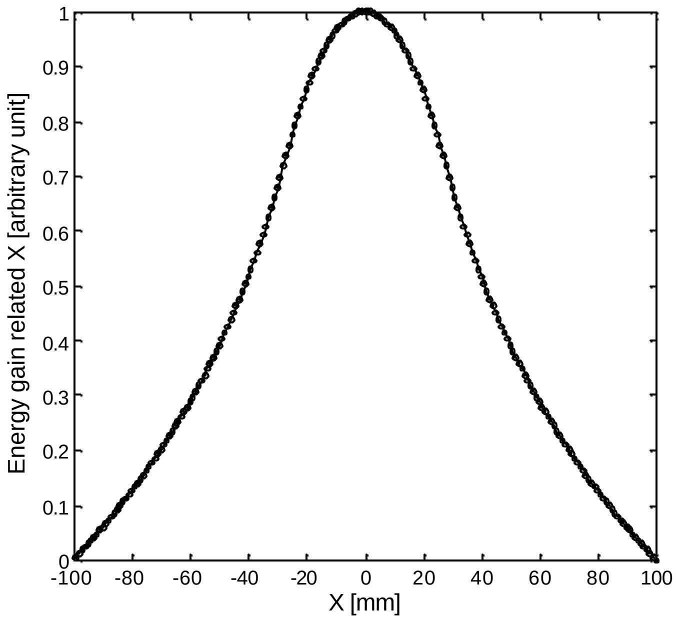
(|X|<a)

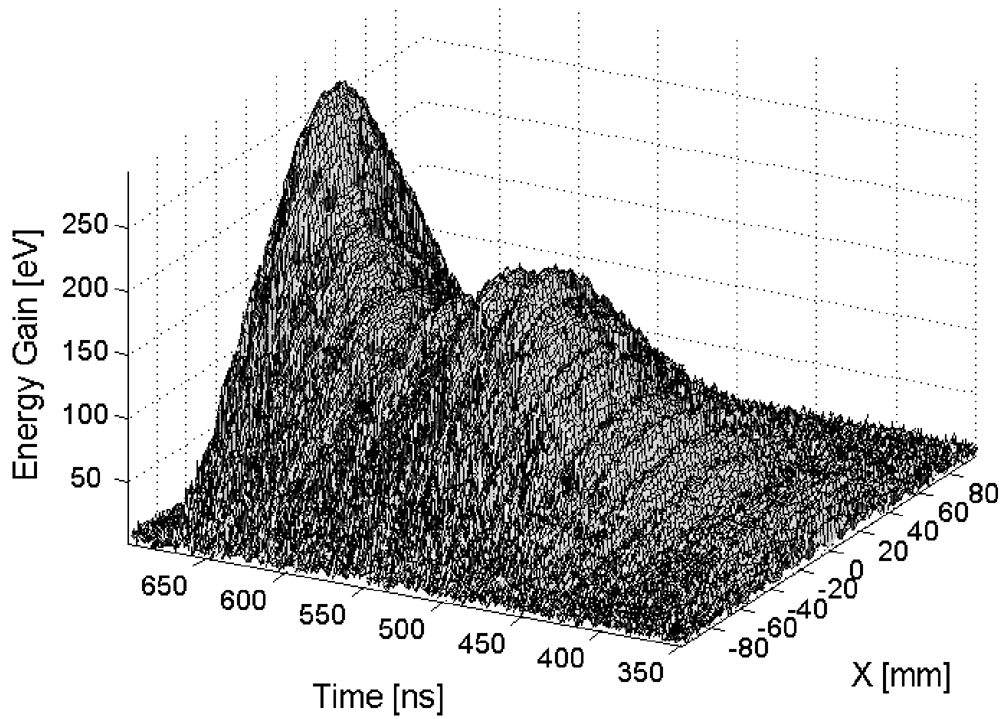
$$\Delta E(X) = -cb\sqrt{\frac{me}{2pe_0}\frac{\partial l}{\partial z}\frac{1}{\sqrt{l}}}\left[\frac{b^2}{X^2}\int_0^{\sqrt{b^2-X^2}}\left(\ln\frac{b^2}{X^2+y^2}\right)^{-1/2}dy-\frac{1}{2}\int_0^{\sqrt{b^2-X^2}}\frac{X^2+y^2}{X^2}\left(\ln\frac{b^2}{X^2+y^2}\right)^{-1/2}dy\right]$$

$$G = \arcsin\left[\frac{\sqrt{a^2-X^2}}{a}\left(1-\frac{\mathrm{X}^2}{\mathrm{a}^2}+\ln\frac{b^2}{X^2+a^2}\right)^{-1/2}\right]$$

(|X|>a)

Electron energy gain in strong dipole magnet

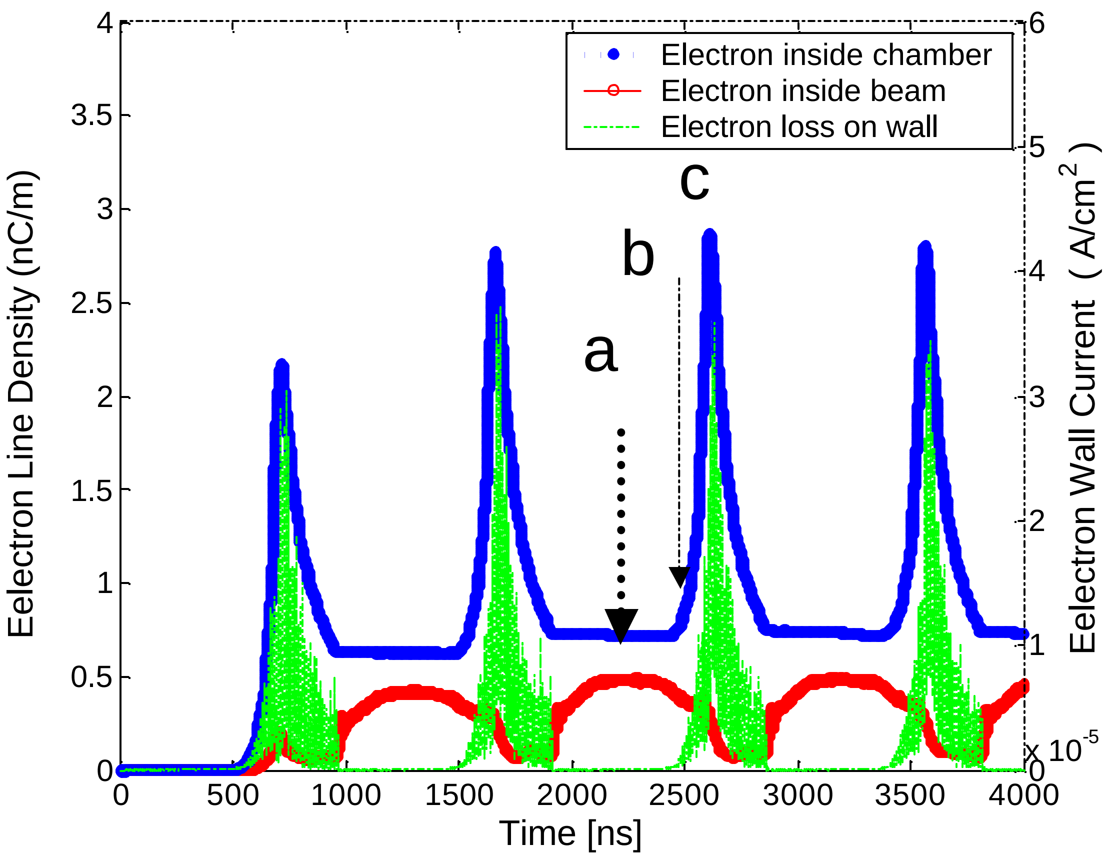


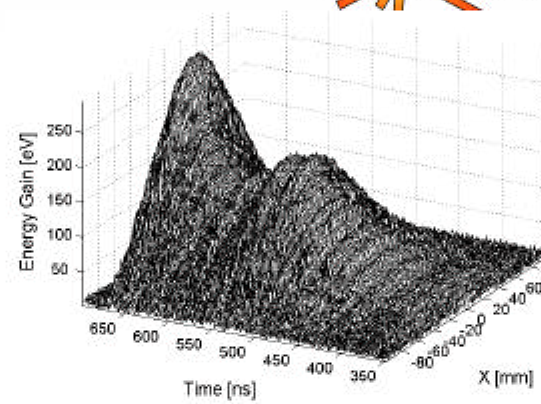


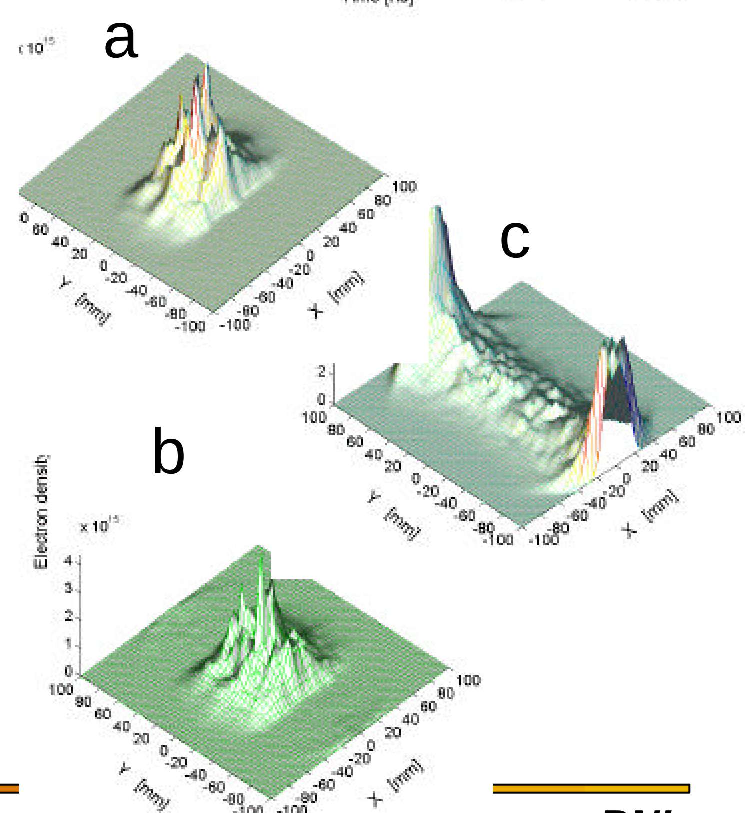
Energy gain at the wall surface for different X-coordinates. Left plot shows the electron energy gain as a function of horizontal coordinate. It is normalized by the peak energy gain at the chamber center X=0. Right plot shows the energy gain of direct drifting electrons in SNS dipole magnets with By=7935 Gauss.

Multipacting in Dipole magnets (By=0.79T)

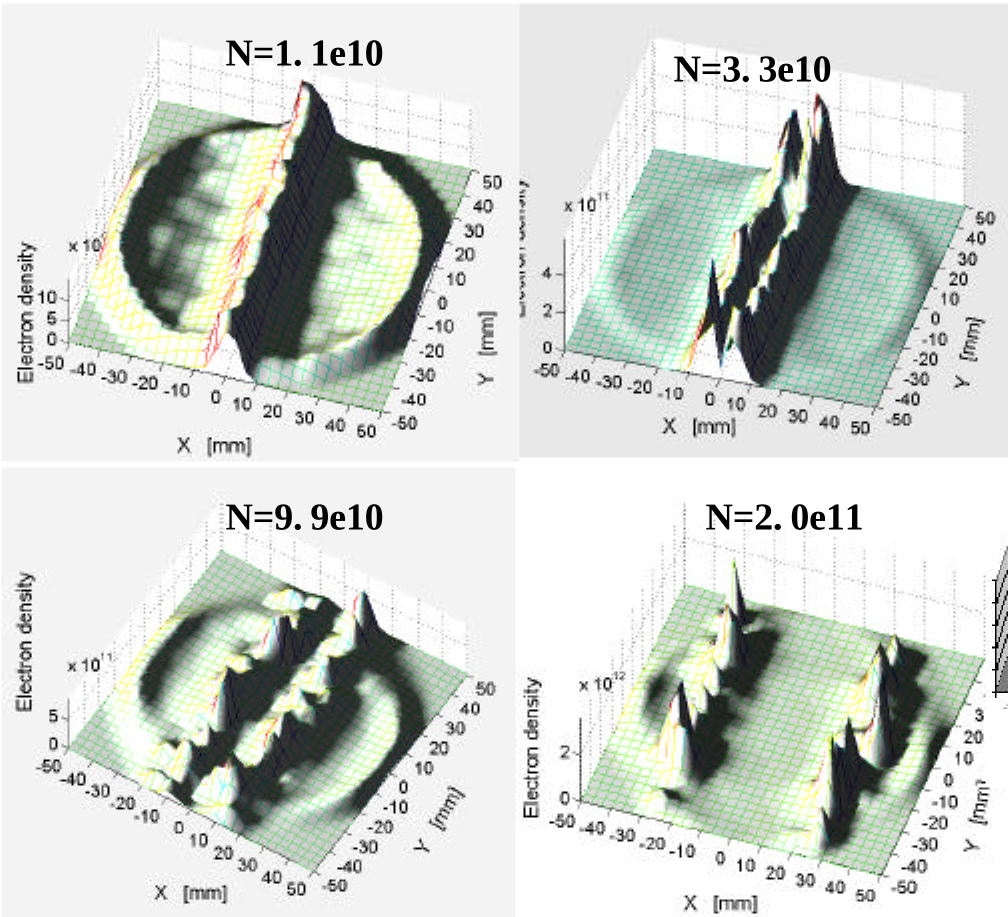
- Multipacting happen at the horizontal chamber center (**1 strip**, agree with estimation)
- E-cloud density is **about 2 times smaller** than the drift region



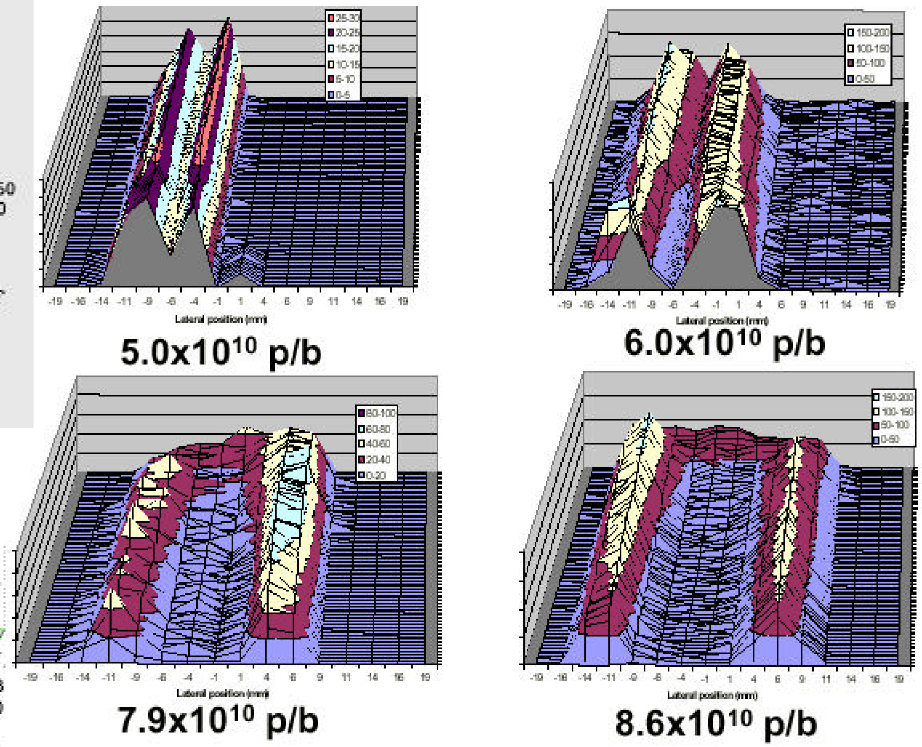




Bunch current effects on Multipacting in *dipole* for **short bunch**---*strip position and lost charge density*



KEKB LER, simulation

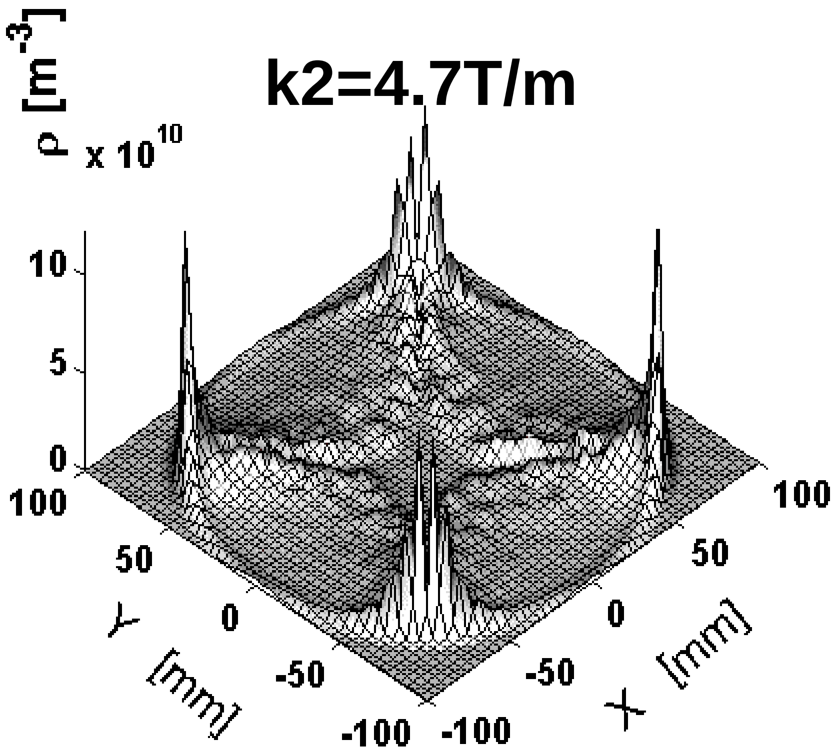


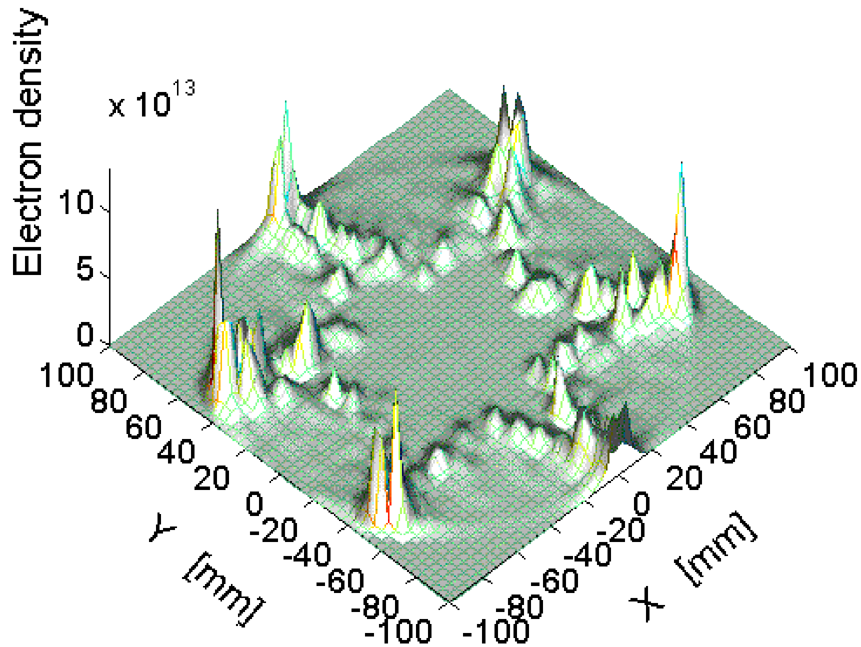
Effect of a dipole field: 2 strips at different bunch intensities, CERN SPS experimental results, J. M.Jimenez, ECloud'02, CERN, 2002

E-cloud in Quadrupole and Sextupole magnets

Ecloud in quadrupole

Ecloud in sextupole





- **Multipacting happens only near the middle of the pole surface**

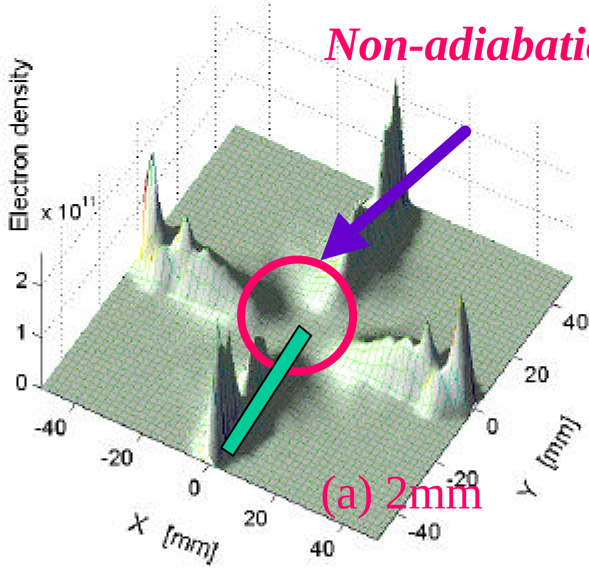
Trapping mechanism-- bunch length effect (PRE,66:036502)

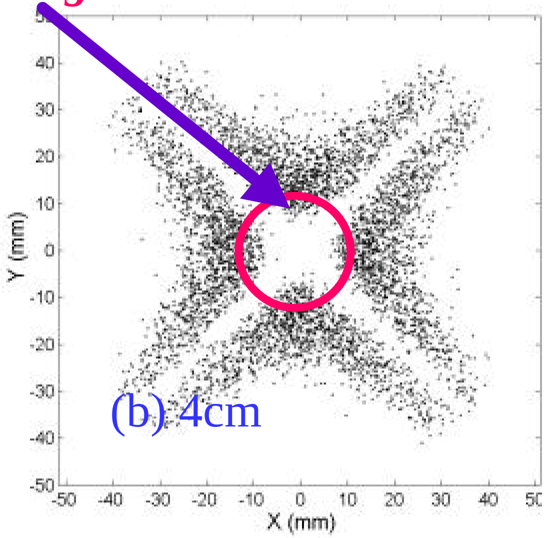
Trap requirement for positron bunch

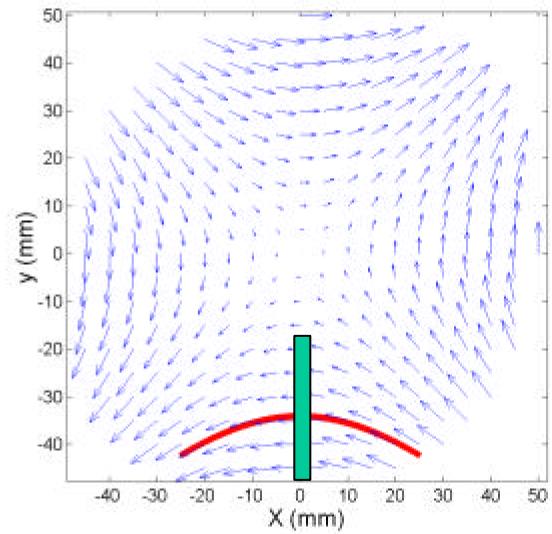
Bunch length should be shorter than period of gyration motion

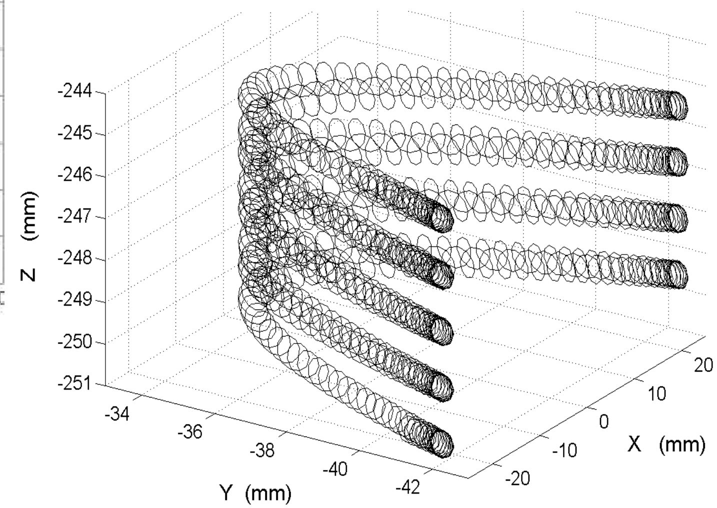
$$s_l < \frac{2\pi cm}{e}\frac{1}{B} \Longrightarrow s_l(mm) < 10.7/B(T)$$

Non-adiabatic region





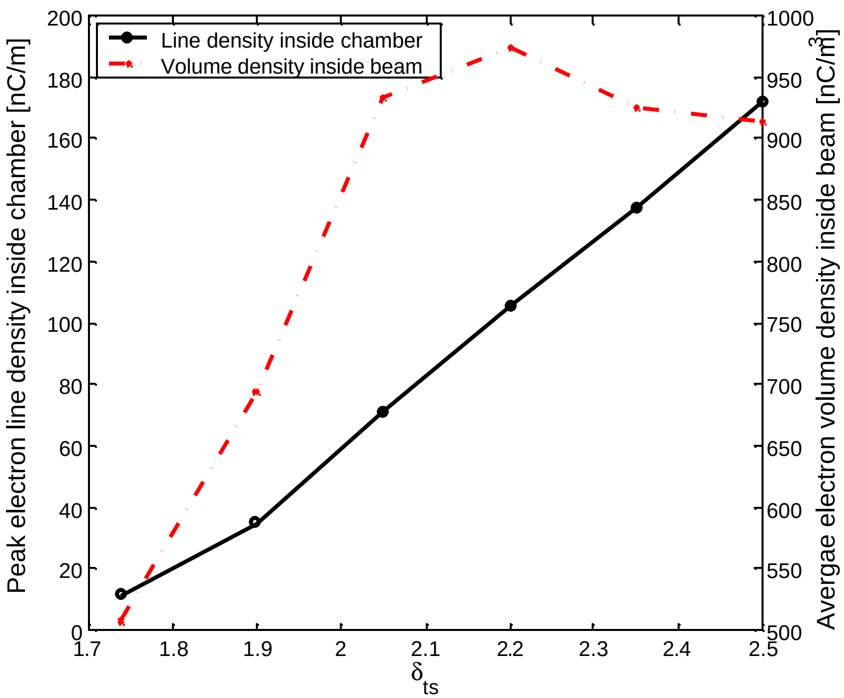


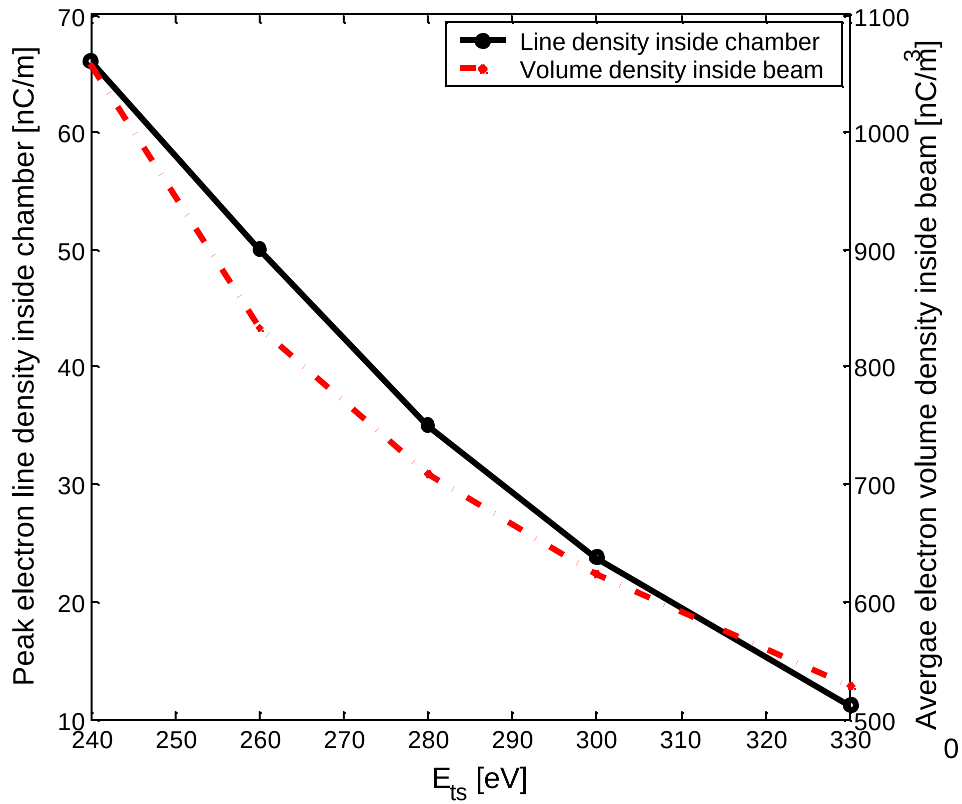


Trapped photoelectron distribution in quadrupole magnet with field gradient 10.3 T/m during the train gap for different bunch length

Peak SEY and Energy at Peak SEY

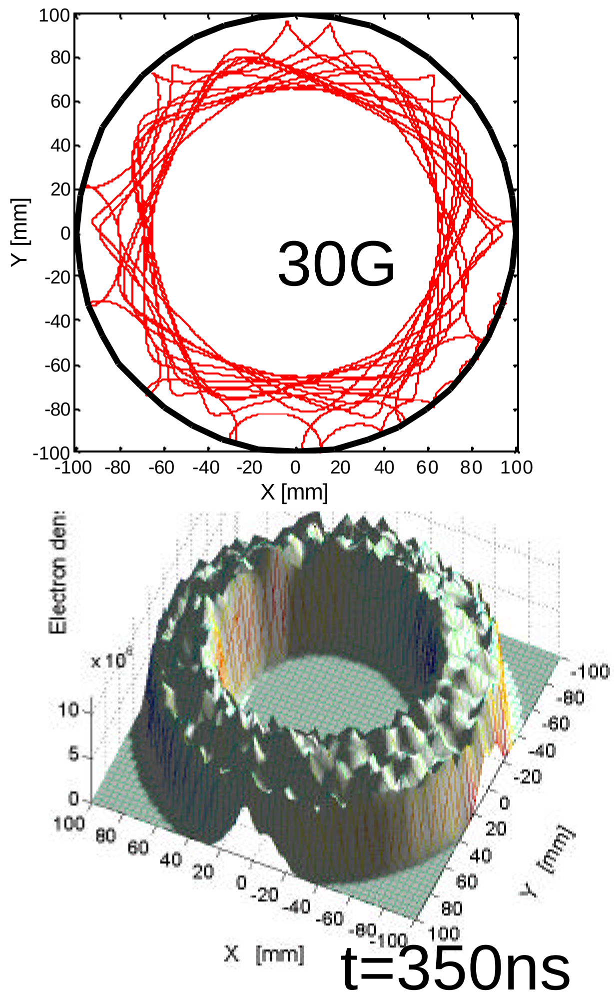
- **E-cloud density inside chamber is a linear function of peak SEY and energy at peak SEY.**
- **E-cloud density inside chamber (and hence Instability growth rate) increases linear with peak SEY and finally saturates at some level.**
- **E-cloud density inside chamber (and hence Instability growth rate) decreases with the energy at peak SEY.**

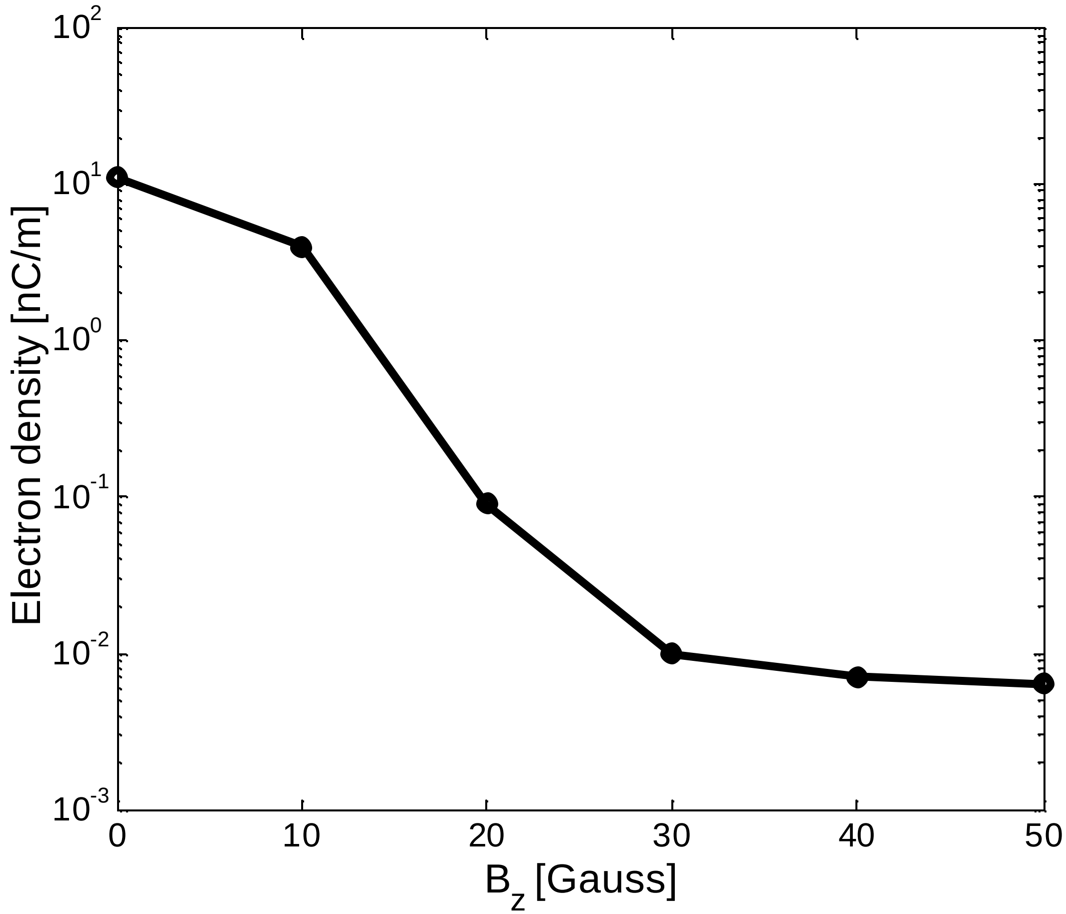




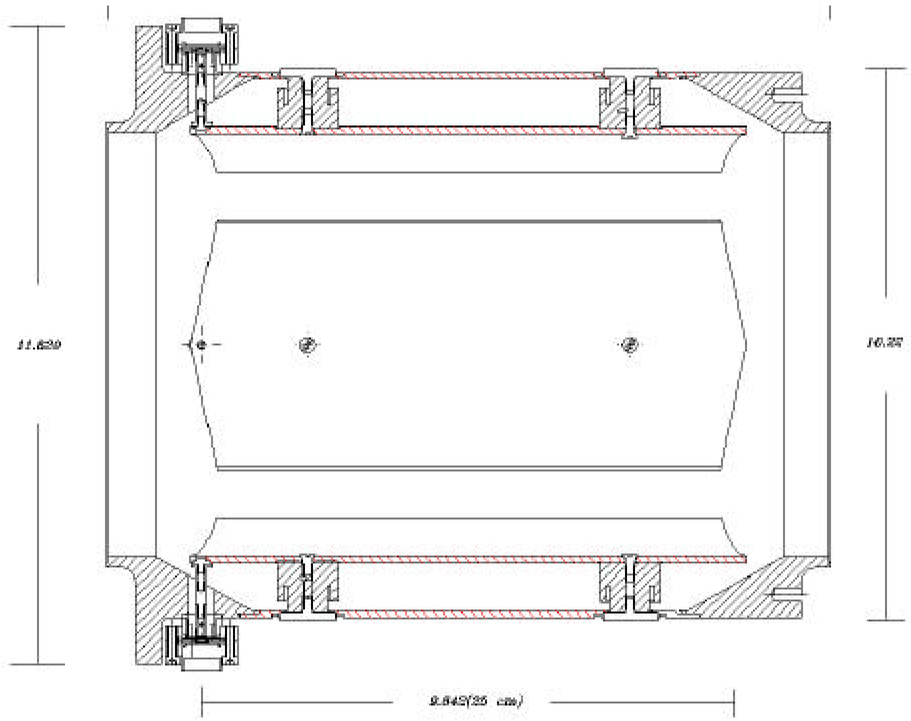
Uniform Solenoid effects

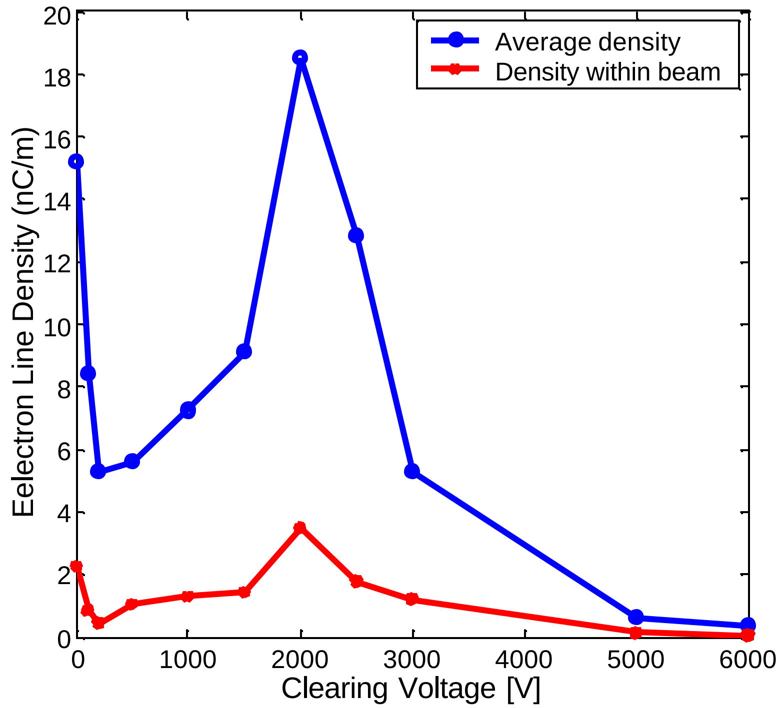
- **30G Solenoid field can reduce the e-cloud density with a factor 2000 !**
- **Zero density within beam**





Electrode clearing effect vs. Clearing voltage (PRSTAB, Vol7:034401,2004)

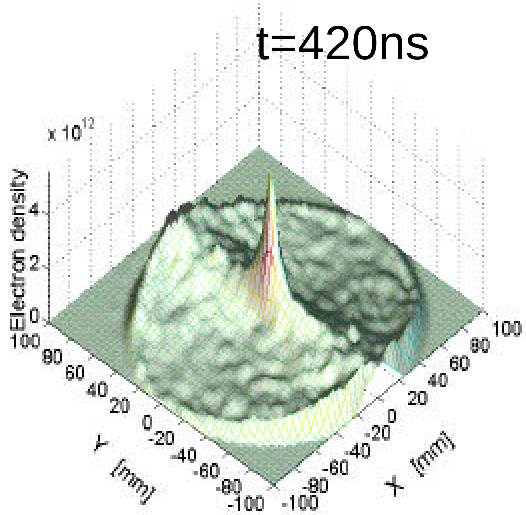


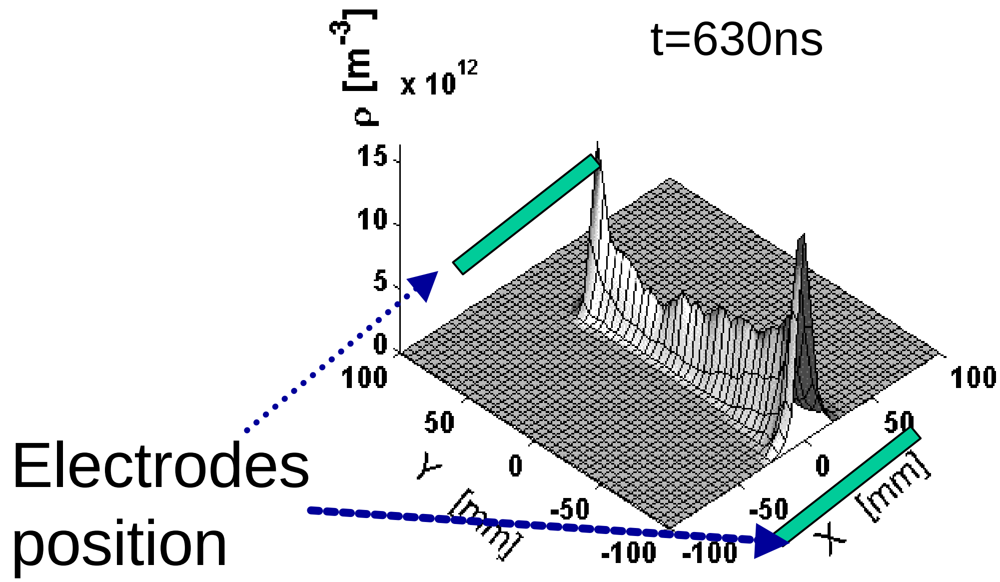


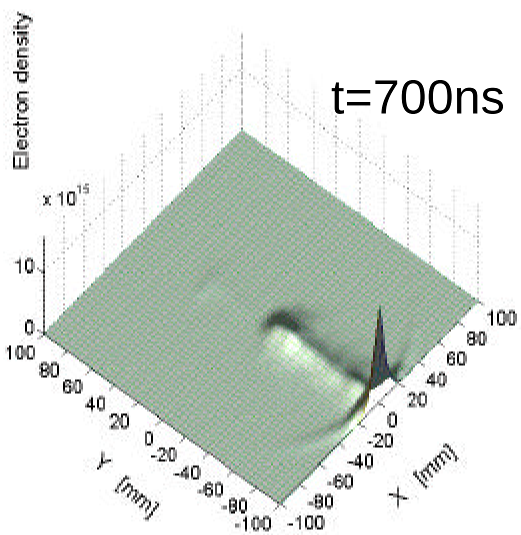
e-cloud density vs. clearing fields

- **Weak field(~200V) is very helpful**
- **Strong multipacting at 2kV, which could be stronger than zero field case**
- **Cooperation with LANL PSR**

E-cloud distribution at different time for 2000V clearing field

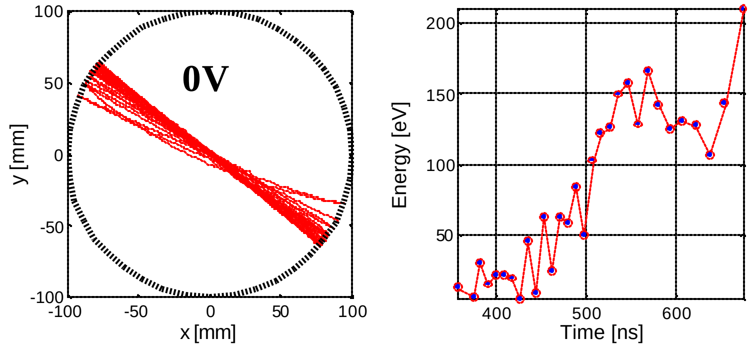


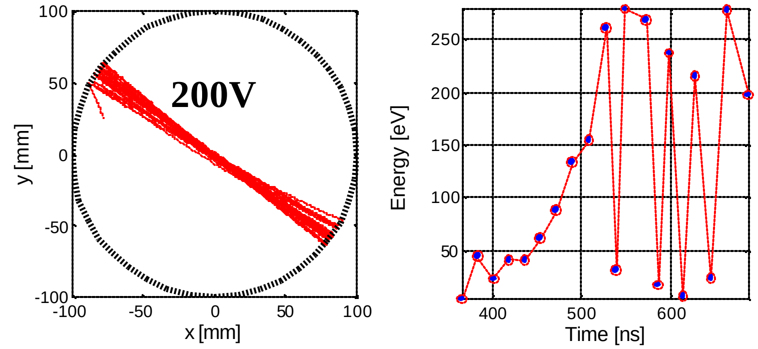




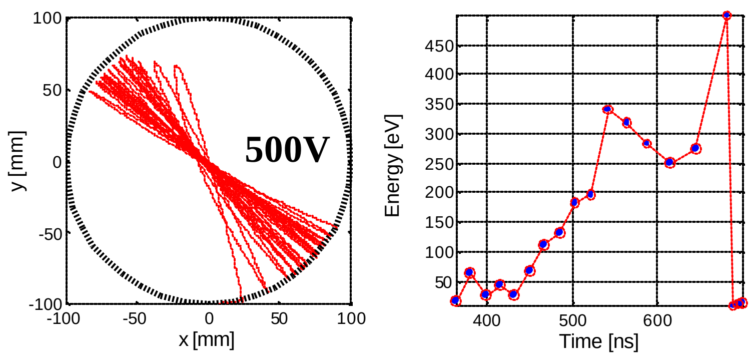
➢**Clearing field can cause the particle polarized toward the clearing field direction. As a result, it causes strong multipacting near the positive electrode.**

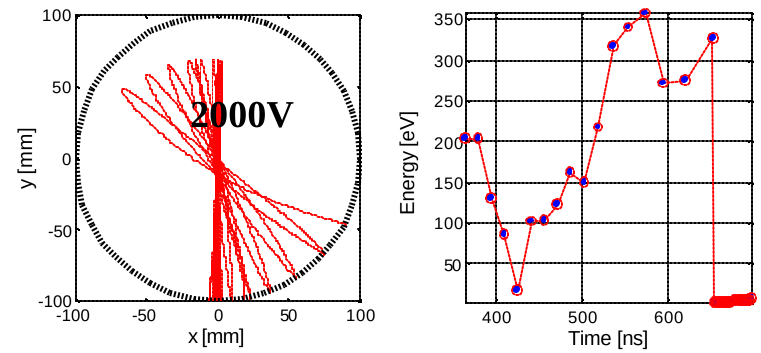
Mechanism of strong multipacting due to clearing field



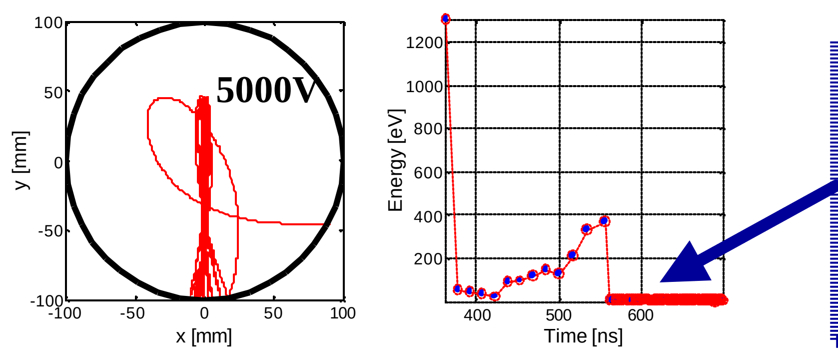


Alternate multipacting





half multipacting frequency



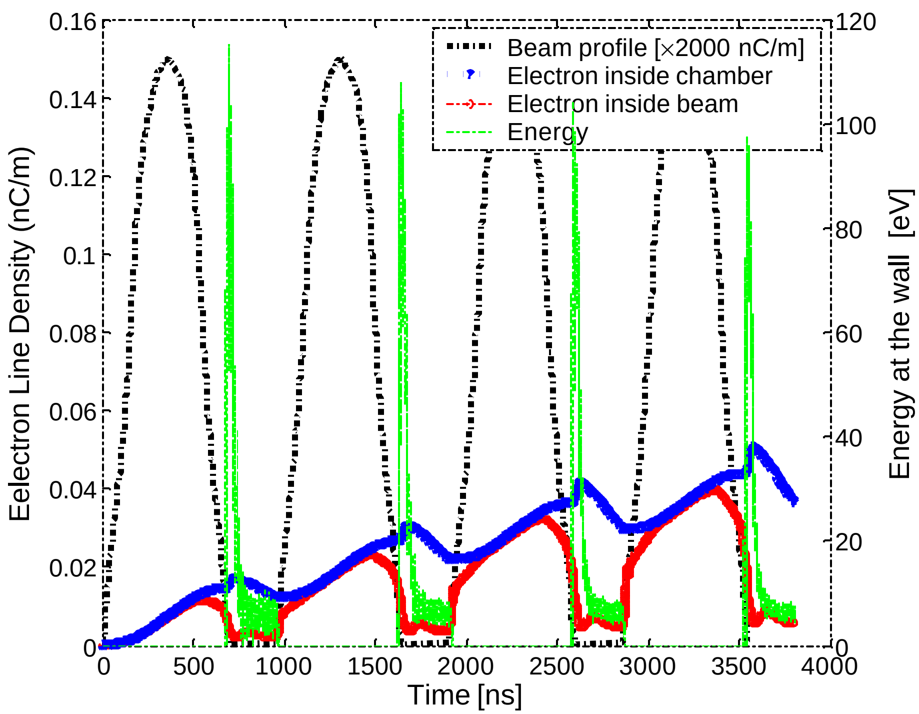
Mechanism of clearing of electron cloud is to suppress the second emission at the chamber surface at the bunch tail. $E_{clearing} > E_{beam}$

Summary

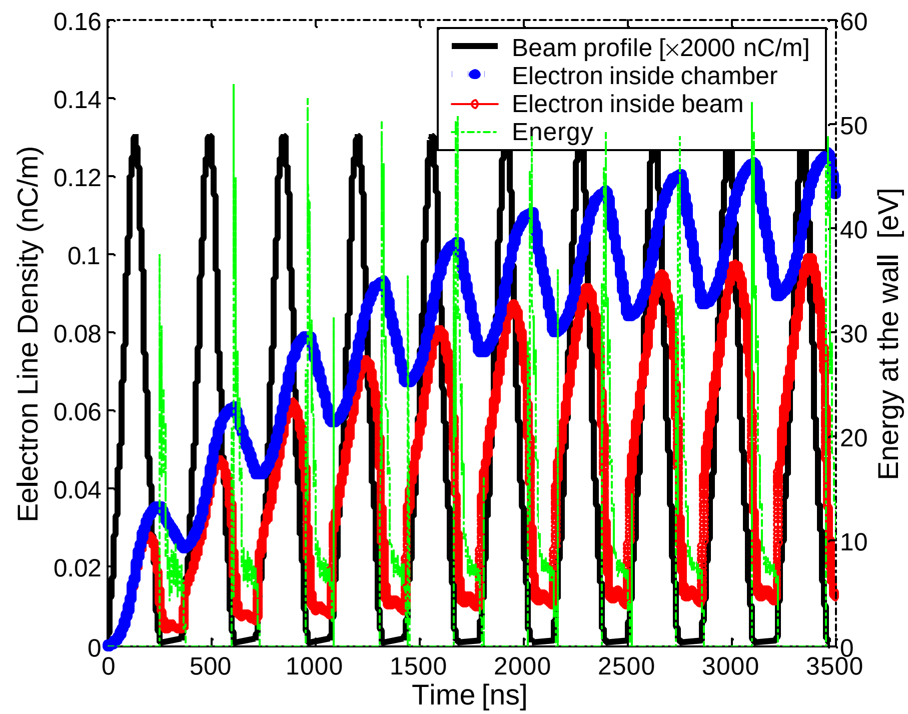
- Mechanism of trailing edge multipacting is clearly explained by Adiabatic invariant, Nonlinear oscillation frequency, electron energy gain.
- Many factors related to the multipacting has been investigated one by one using 3D code. The results qualitatively agree with the our analysis and experiment studies. Beam intensity, Longitudinal beam profile, transverse beam size, beam in gap are important.
- Strong multipacting at horizontal chamber center of dipole magnet.
- Solenoid is a good remedy (convenient and effective)
- Clearing electrode is complicated. Electrode is helpful for the clearing of trapped electrons and hence instability

Thank you for attention!

Electron by ionization



SNS beam

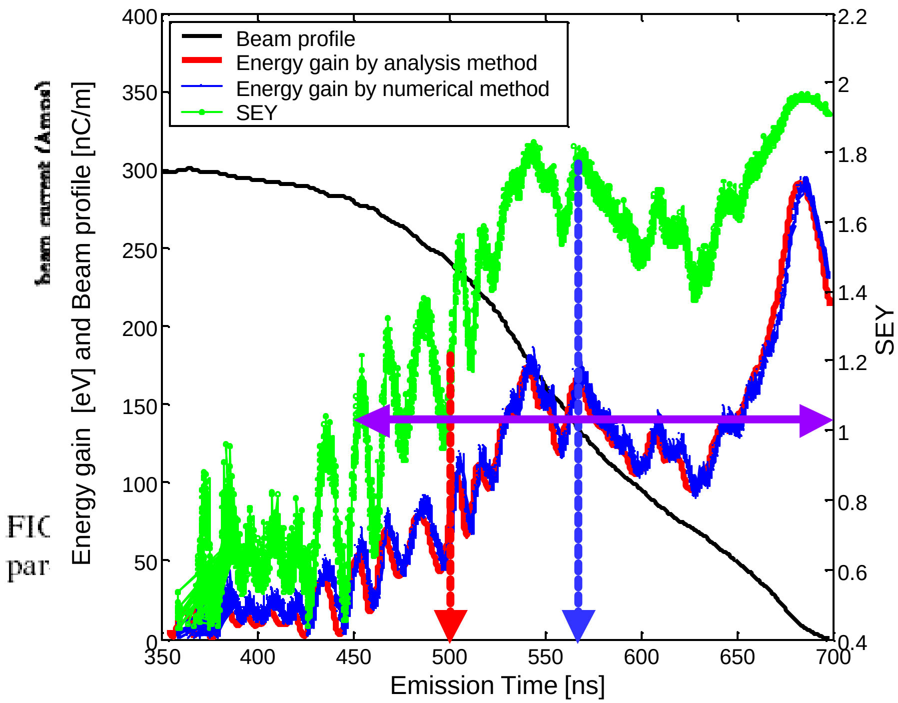


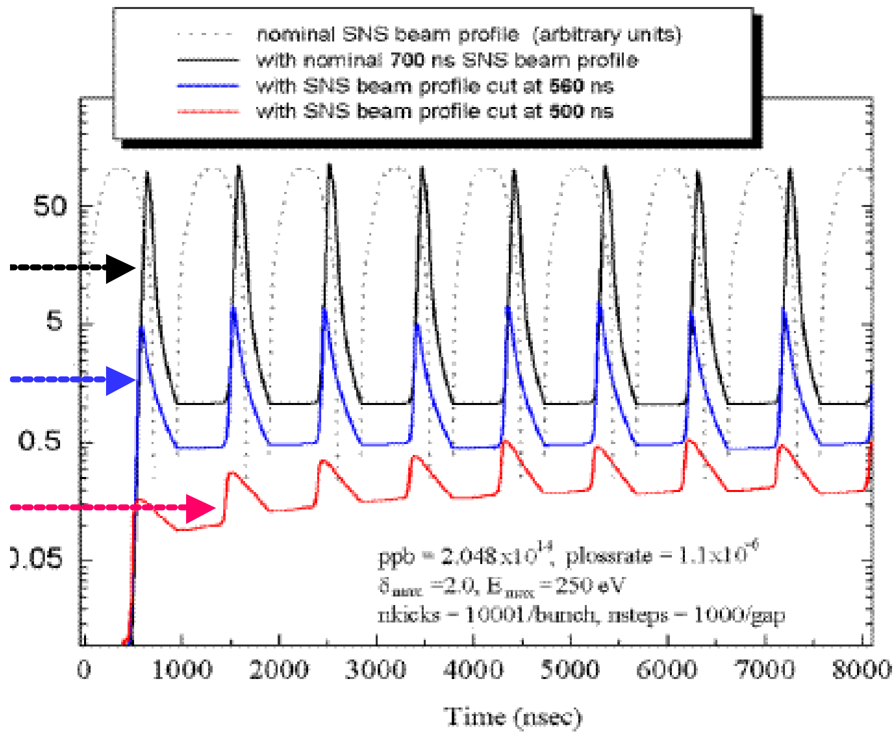
PSR beam

- ❑Assuming the same yield as the yield due to proton loss
- ❑Electrons due to direct ionization can be neglected for long bunch due to the long term trapping and low energy gain

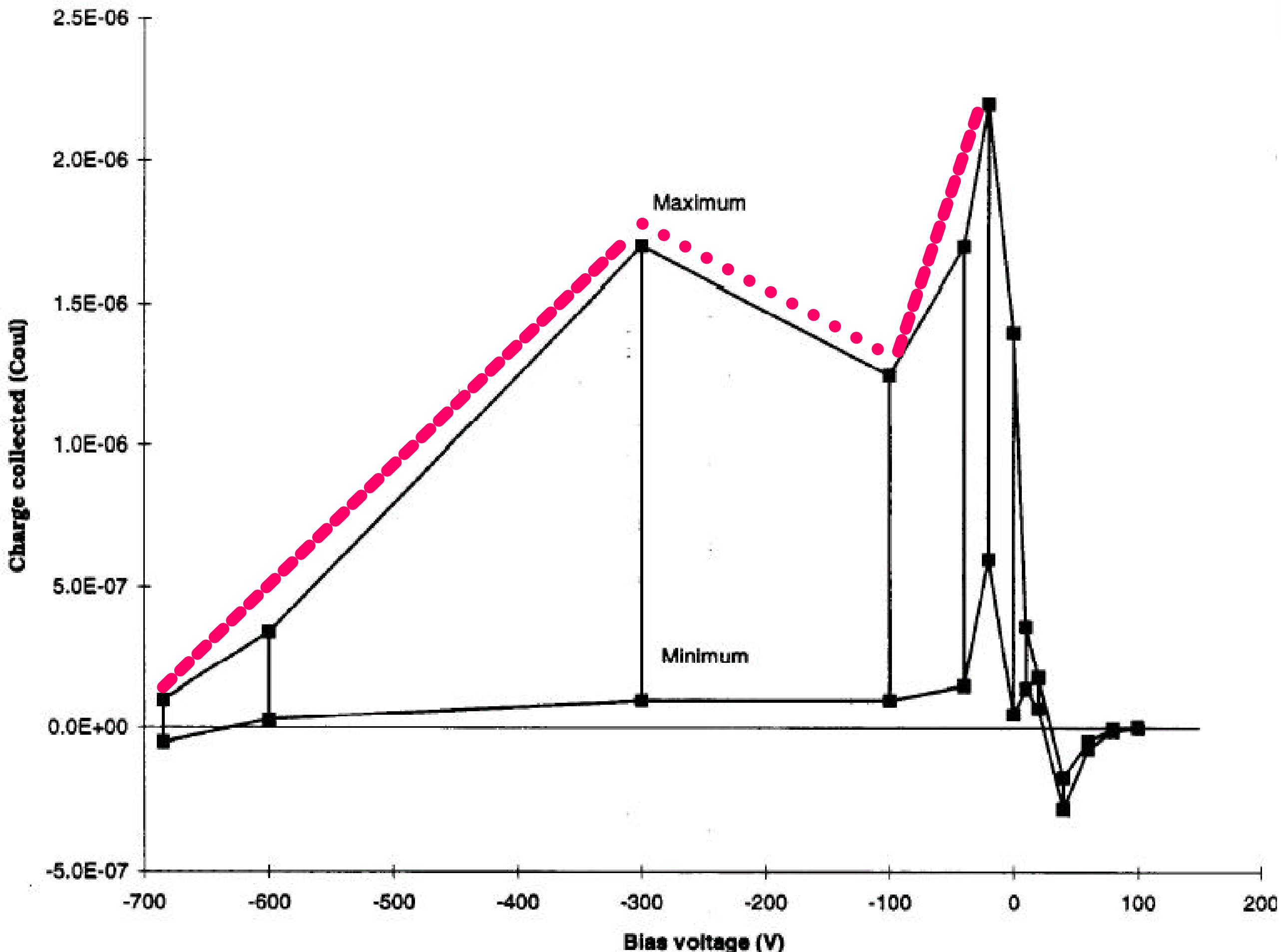
Longitudinal Profile effect, simulation

The longitudinal beam profile's effect was demonstrated by simulation (M.T. F. Pivi and M. A. Furman PRSTAB Vol. **6**, 034201 (2003))





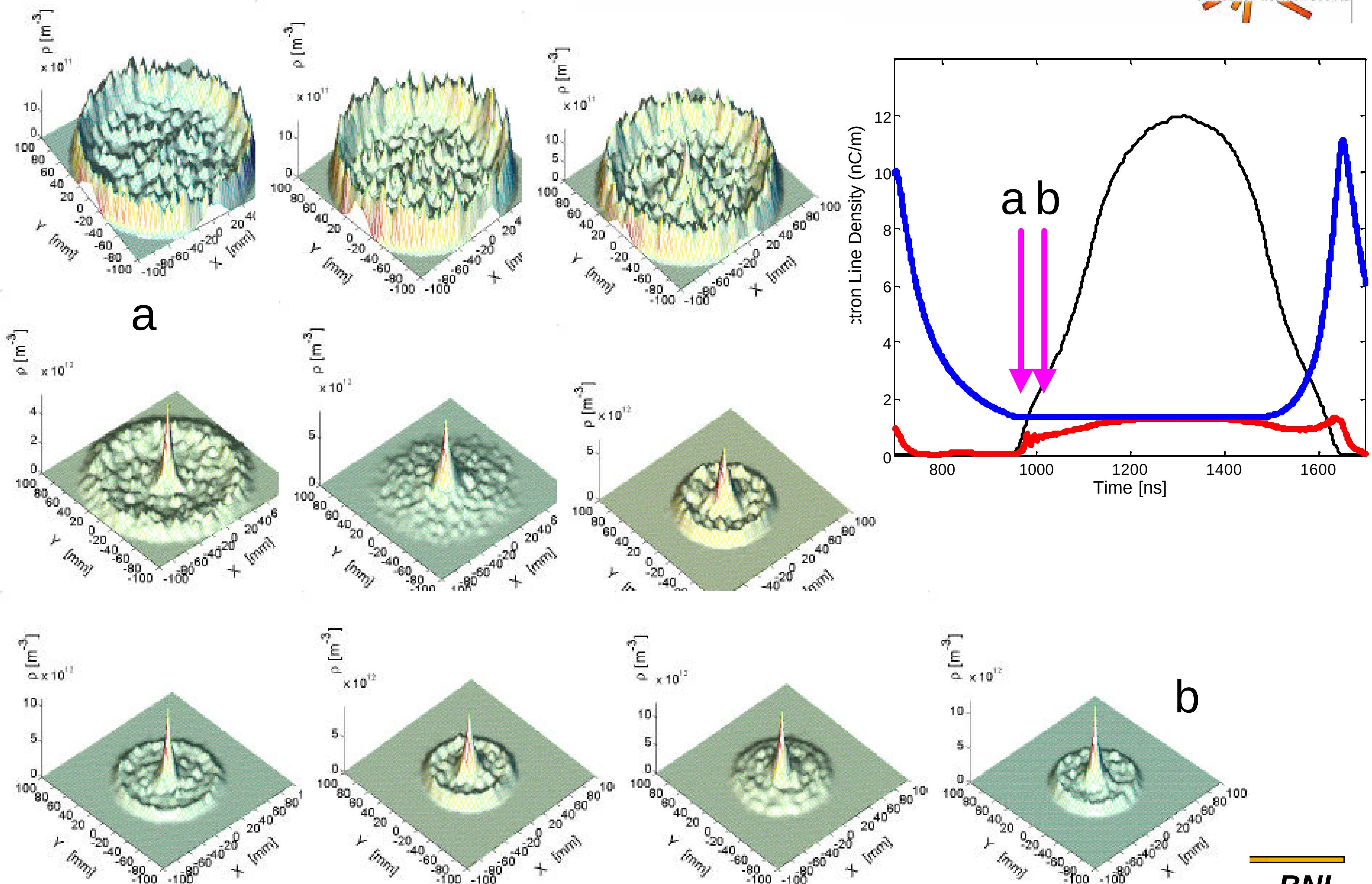
PSR(PSR-94-03,M. Plum, etc.)



700V 0V

PSR experiment

Snapshot of first 70 ns



BNL

Transverse Beam Size Effects

- A smaller beam size contributes to stronger space charge field and hence larger electron energy gain and stronger multipacting.
- Instabilities is sensitive to *a*. Small *a*, strong instability

$$l_{chamber}[nC/m] = 21 - 0.27a[mm]$$

$$r_{cen}[nC/cm^3] = 4.9e^{-0.1a[mm]}$$